ESTIMATION OF POTENTIAL YIELD USING REMOTELY SENSED PARAMETERS ALONG GUJARAT, NORTHWEST COAST OF INDIA

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Contents

Sl. No.	Content	Page No.
1	General Introduction	1-5
2	Review of Literature	6-9
3	Passive geo-referencing and validation of historic commercial fishing grounds and estimated catch data off Gujarat using data available with CMFRI	9-15
4	Estimate Primary Productivity of the sea off Gujarat by developing suitable models	16-23
5	Develop suitable models and estimate the Fish Yield of the sea off Gujarat	23-31
6	Summary and Conclusion	31-35
7	References	35-42
8	Immediate outputs and outcome of the research	43-59

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1. General Introduction

Oceans are critical elements on the globe by their vast occupancy and key roles such as climate stabilizer, supporting critical biodiversity and fishery resources. The marine fishery resources mainly serve as a rich source of animal protein and contribute significantly to the global nutritional security, employment generation and also are an important livelihood option for the coastal fisherfolk. Interactions in the marine ecosphere are complex and are important, especially with fisheries resources. These interactions need to be studied to estimate, manage and to forecast the fishery of the region. To initiate such studies, data on the spatial and temporal distribution of the fishery is a prerequisite. Such data would enable one to understand the behavioral dynamics of fishers, differential fishing intensity at various locations and seasons, varied effects on the marine ecosystems to assess the potential effects and for framing management interventions (Turner et al., 2015; Salas and Gaertner, 2004). Few studies on the importance of spatially and temporally explicit data on small-scale fishing activity have been made in various parts of the globe (Daw, 2008; Dunn et al., 2010; Dineshbabu et al., 2019). Imposition of fishing restrictions and other regulations have changed the structure and dynamics of local fishery practices, with inshore fishing effort partially reallocated to offshore fishing grounds farther from port (Sandra and Goni, 2019).

The hydrographic features in the ecosystem govern the production and show pronounced seasonal variations. Primary production (PP) represented mainly by the marine phytoplankton is a source of energy. The process of primary production (PP), not only fuels biological growth and fish productivity but also regulates the carbon uptake and release by the ocean (Falkowski, 1988). The data generated by satellite ocean color sensors provides a synoptic view of the physico-chemical and biological changes with higher resolutions of spatial and temporal scales (Werdell et al., 2003). The ability to estimate the PP at higher temporal and spatial scales has revolutionized the ocean color remote sensing and is now almost on par with the data provided by *in-situ* techniques, but

frequent validation tarils were required for various sensors (Eppley et al., 1987; Antoine et al., 1996; Joo et al., 2016). Globally, over twenty models have been developed to estimate the PP, and it runs solely using remotely sensed data for diverse ocean ecosystem studies (Kameda and Ishizaka, 2005; Campbell et al., 2002; Carr et al., 2006; Friedrichs et al., 2009; Saba et al., 2010 & 2011; Tilstone et al., 2015; Lobanova et al., 2018). In addition, several models and parameters have been proposed to estimate vertically integrated primary production (Behrenfeld & Falkowski, 1997b, Platt et al., 1991).

The holistic or analytical models for single fish species were used widely to estimate the potential yield and evaluate the status fish stocks. The holistic models like the surplus production models (Schaefer, 1954; Fox, 1970) or the analytical models (Thomson and Bell, 1934; Beverton and Holt, 1966) applied to various fisheries across the world to evaluate the stock status and subsequently propose the reference limits (Potential Yield, PY). The single-species models are having limitations while computing scientifically reliable management reference limits, especially in case of multi-species fishery like India. Hence, an entire ecosystem approach (using EwE) was attempted to estimate the potential yield for the marine fisheries of Gujarat in addition to surplus production models. An ecosystem-based approach to fisheries management (EAFM) takes into account the interactions between species, ecosystem and fishery resources (Parsons and Harrison, 2000). The central principle of an ecosystem-based approach to fisheries management is the recognition that fishery yields are ultimately limited by ecosystem primary production (Pikitch *et al.,* 2004). The environmental mechanisms that determine the magnitude of ecosystem-level production have received a great deal of attention as these data are necessary to predict future fishery yields.

1.1.Scope of the Study

Globally, the marine fishery research is heading towards a spatial management approach. Developed countries have several fishing effort management interventions such as logbook system (catch reporting), Vessel Monitoring System (VMS), Monitoring, Control and Surveillance (MCS), Automatic Information System (AIS) for monitoring the fishing and efficient management of the fishery resources. India, a developing country is yet to initiate and implement such fishery management techniques and thus is yet to

understand the spatial and temporal spread of fishing grounds. Knowledge on the extent of resource abundance and fishing effort by various crafts at temporal and spatial scale are vital for framing sound management strategies and policies. In India, the maritime state of Gujarat, possesses the longest coastline (>1600 km), widest continental shelf (1, 84,000 km^2) and contributes to nearly 22% of the total marine fish landings of the country. The registered number of fishing crafts existing in the sector in Gujarat are high, comprising of mechanized (16,377), motorized (10,894) and non-motorized (76) (ReALCraft, 2018). The present study intended to map the fishing grounds across different crafts for different zones and seasons. The mapping of spatial and temporal activities by different fishing crafts will be baseline database in marine spatial planning and also useful to coastal and marine security agencies. Further, the database on a GIS platform will be very useful while formulating fishery management plans (FMPs), declaration of no-fishing zones, and marine conservation policies.

The marine primary productivity is the proxy to global carbon budget analysis and will provide insights to ecosystem productivity at temporal and spatial scales. The data collected through satellite ocean color sensors provides a synoptic view of the physico-chemical and biological changes in the ocean with higher scales of spatial and temporal resolutions (Werdell, 2003). The major bottleneck in understanding the biogeochemical processes in the ocean is the limited *in-situ* data collected during onboard cruises and other available ocean-based platforms for data analysis. The research attempt made to assess the evaluation of performing satellite data products (Chlorophyll-*a* and Primary Productivity) in the region with *in-situ* data matchups. The spatial and temporal variations in PP (mg C m^{-2} day^{-1}) in the northern Arabian Sea during 2015 to 2017 (monthly average) retrieved from the VGPM model to identify and tag productivity seasons and zones. The principal aim of the study is to validate the existing algorithms with the regional parameterization and define the most accurate model for the northeastern Arabian Sea. The study also strengthen the *in-situ* PP database (spatially and temporally) with advance methodologies to validate global models, to develop appropriate regional algorithms and develop models that could be used in the applied research.

Knowledge on the marine fishery potential yield for the region is crucial for sustainable exploitation and management of resources; propose optimum fleet strength and framing appropriate policies by the government. The estimation of potential yield from a fishery in not a straightforward exercise, rather a complex process or endeavor. The first objective defines the study area based on the distributional extent of major fishery resources or the expanse of fishing ground. The georeferencing of the fishing ground could provide the critical input on the area under exploitation by the fishing fleets of Gujarat, which can be adopted as the study area. The potential yield can be arrived at using various approaches, the one which gives high consideration to inter-species interaction is the EwE model. The primary productivity forms the key input in the model as it forms the base of the trophic food chain. The estimates of *in-situ* PP and modelled PP from the regionally parameterized algorithms was used in the EwE model while computing potential fish yield. The present study adopted a multi-model (BSM, CMSY and EwE) approach towards the estimation of the potential yield of commercially important fishery resources exploited by a fleet of Gujarat.

Scientific information on the availability of marine fishery resources, estimation of potential yield and existing interactions in the ecosystem are useful inputs in the fishery management plans (FMPs). This information would enable judicious exploitation and to sustainably manage the resources. Schaefer's surplus production model is applied to the time series catch and effort data across the commercially important groups, to work out the potential yield. The EwE analysis was used, wherein the *in-situ* primary productivity and gear-wise fishery data for the identified functional groups were considered while estimating the potential yield. Estimation of marine fishery potential yields for the region is crucial for sustainable exploitation, allocation, and management of resources, propose optimum fishing fleet and its management, for framing policies by the government. Overall, the current research aims at geo-referencing the historic fish landings data, spatio-temporal mapping of fishing by various fleet, develop and validate primary productivity algorithms, and also to estimate the potential fish yield off Gujarat along the north-west coast of India with various models developed.

1.2.Objectives

1. Passive geo-referencing and validation of commercial fishing grounds and estimated landings off Gujarat using time series data available with CMFRI.
2. Develop suitable models to estimate the marine Primary Productivity off Gujarat.
3. Develop suitable models and estimate the marine Fish Yield off Gujarat.

1.3.Area and period of the study

The Arabian Sea region in the Indian Ocean is one of the most productive regions compared to any other ocean in the world (De Sousa et al., 1996). The northeastern Arabian Sea (NEAS) forming the northwest coast of India's Exclusive Economic Zone (EEZ) and the current study area located in the NEAS. The study area is known for its unique circulation pattern, coastal upwelling, winter convective mixing, making the region very productive. Monthly on-board scientific sampling cruises were made at off Veraval and off Okha in Gujarat, to collect *in-situ* data for three years during 2015 to 2017 (Figure 1). Samples were collected from 204 locations during the study period. Data sets on seasonal variations in the Primary Productivity (PP) and Chl-*a*, were sorted into four seasons (Raman, 2013) as a) winter monsoon (December-March), b) spring inter-monsoon (April-May), c) monsoon (June to September) and d) fall inter-monsoon (October-November).

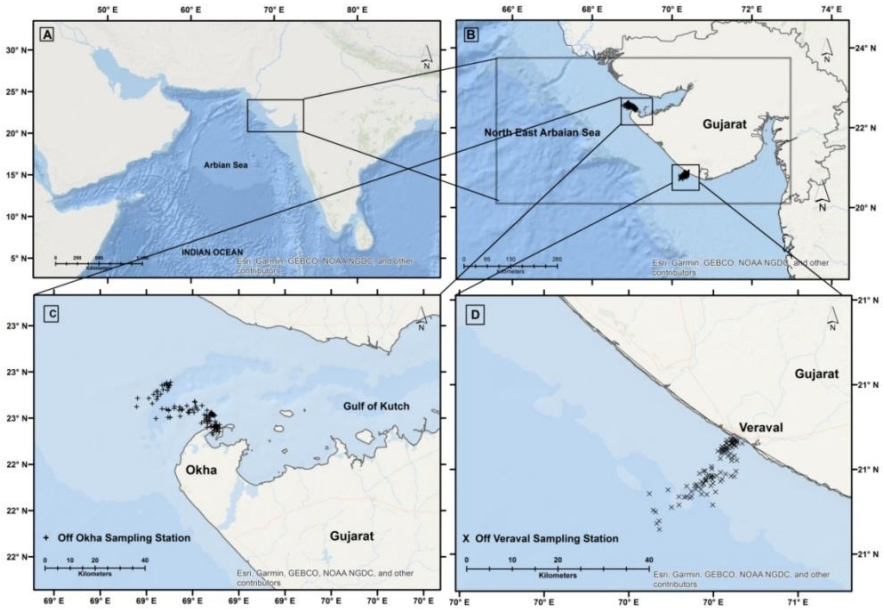


Figure 1. Map of the study area- Gujarat (northern Arabian Sea) showing the two sampling stations off Veraval and off Okha

2. Review of Literature

2.1. Passive geo-referencing of fishery data on spatial and temporal scale

Globally, the catches from the fishing zones are reported either as catch per day, catch per hour or as catch per trip (NMFS, 1996). Spatial data have been used in marine fisheries research across the world. These works include studies on the feasibility of a region-wide fishery-independent monitoring (FIM), probability survey of coral reef fishes in Puerto Rico and the U.S. Virgin Islands (Bryan et al., 2016) and cross-shelf occupancy probabilities for juvenile groupers in the Florida Keys (Harford et al., 2016). Studies were also attempted to geo-reference catch and effort data, influence of environmental variables on catch rates of the pink shrimp, *Farfantepenaeus duorarum* and also map the Essential Fish Habitats (EFH) in West Florida Shelf (Rubec et al., 2016b), map gillnet fishing grounds and predict the spatial distribution and abundance of the southern Flounder (Froeschke and Froeschke, 2016), geographic and depth distribution of species, life history characteristics, exploitation patterns and vulnerabilities in the Gulf of Mexico (Farmer et al., 2016). A spatial model was developed for life stages of 87 commercially important species in Tampa Bay (Rubec et al., 2016a).

Studies on the importance of spatially and temporally tagged data on small-scale fishing activity have been reported from various parts of the globe (Salas et al., 2007; Dunn et al., 2010; FAO, 2015; Thiault et al., 2017; Sandra and Goni, 2019). In India, a pilot attempt on the mapping of fishery resources and fishing activities along the Indian coast was significantly made by ICAR-CMFRI (Dineshbabu et al., 2012a; CMFRI, 2018; Lawrence and Bhalla, 2018; Jyoti et al., 2018; Koya et al., 2018; Dineshbabu et al., 2019). Methodologies were developed for the mapping of fishing activities and these maps have served as a baseline and efficient tool for marine geospatial and temporal studies by researchers, shipping industry, national security, defense services, planners, policy makers, etc (CMFRI, 2017; Dineshbabu et al., 2016).

2.2. Validation of primary productivity of the marine waters

The global oceans absorb more than half of the earth's carbon by photosynthesis, and also known for their roles in carbon sequestration and support of marine biota. The estimation of the magnitude and the rates of ocean PP on global and regional scale are

key factors to understand the role of the ocean in the Earth's carbon cycles (Prasad and Haedrich, 1994). The ability to estimate the PP at higher temporal and spatial scales has been revolutionized by the ocean color remote sensing and made it on par with the data provided by *in-situ* techniques (Eppley et al., 1987; Joo et al., 2016). The ocean color remote sensing satellite can now estimate chlorophyll-*a* concentration accurately, wherein the optical properties are controlled mostly by phytoplankton (Murakami et al., 2006). The primary productivity can be estimated from the satellite-derived data, i.e., surface chlorophyll, sea surface temperature (SST) and photosynthetically available radiation (PAR) (Longhurst et al., 1995). Several models and parameters have been proposed to estimate vertically integrated primary prodictivty (Behrenfeld and Falkowski, 1997a; Campbell et al., 2002; Carr et al., 2006).

The diverse models have been developed to estimate the PP and all these models are run solely using remotely sensed data for the different ocean ecosystems. A few of these models have been validated to find out their relative or absolute accuracy (Behrenfeld and Falkowski, 1997b; Platt et al., 1991; Kameda and Ishizaka, 2005; Campbell et al., 2002; Carr et al., 2006; Friedrichs et al., 2009; Saba et al., 2010, 2011; Tilstone et al., 2015; Lobanova et al., 2018). The ability of 36 models were tested to estimate the decadal trends in NPP at two time-series stations in the North subtropical gyres of the Atlantic and Pacific Oceans (Saba et al., 2010). The Vertically Generalized Production Model (VGPM) was applied for the satellite-data with *in-situ* primary production data and it explained only 40% of the variability in the Sagami Bay, Japan. The *in-situ* measurements during cloudy days point out that the use of satellite data on sunny day's overestimates primary production (Ishizaka et al., 2007). Various researchers have studied the seasonal variations in physical and chemical characteristics, nutrient dynamics in the network of coastal and offshore waters across India, but very minimal research was done on validation of satellite sensors for the computation of PP (Mathew and Pillai, 1990; Sridhar et al., 2006; Manikannan et al., 2011; Latha et al., 2013; Raman, 2013; Temkar et al., 2015; Vase et al., 2018).

2.3. Estimation of potential yield for the marine fishery resources

The maximum sustainable yield (MSY)/potential yield (PY) is the highest equilibrium harvest that could be extracted from the system and ensures the greatest

theoretical yield from the system (Gulland, 1983; Hilborn and Walters, 1992). The global fisheries potential yield from the marine system has been estimated by several researchers by adopting different approaches and different figures ranging between 22 and 1400 million metric tonnes has been proposed (FAO, 1953; Schaefer, 1965; Ricker, 1969; Ryther, 1969; Gulland, 1971; Moiseev, 1994; Chapman, 1965; Lehodey et al., 2003). Earlier studies by Raghu Prasad et al. (1970) and Jones and Banerji (1973) have estimated the fishery potential of the Indian Ocean based on primary productivity and catch trends. Besides, several attempts have been made by working groups to estimate the potential yield of marine fisheries form the Indian Exclusive Economic Zone (EEZ) using multiple approaches (DAHDF, 2011, 2018). The potential yield estimation using the Surplus production model either in linear or non-linear form has been applied to several fisheries in the Indian EEZ (Balan and Sathianandan, 2007; Sathianandan et al., 2008; Sathianandan and Jayasankar, 2009; Najmudeen et al., 2014; Sreekanth et al., 2015) and provide management advisories to regulate or optimizing fishing effort to sustain resources.

The single species models i.e. either holistic or analytical was used widely to compute the maximum sustainable yield and to know the status of fish stocks (Schaefer, 1954; Fox, 1970; Thomson and Bell, 1934; Beverton and Holt, 1966) and applied to various fisheries across the world ocean to propose the reference limits. In addition to the Bayesian Surplus Production model (BSM) and Catch-MSY models, we intend the complete ecosystem models to incorporate all the components of the ecosystem across all trophic levels right from the primary producers to the apex predators. The most widely used complete ecosystem models are ECOPATH (Polovina, 1984; Christensen and Pauly, 1992), ECOSIM (Walters et al., 1997) and ECOSPACE (Walters et al., 1999). The EwE is basically a steady-state model, and the linear function of models can be converted into differential equations leading to ECOSIM which provides dynamic mass balance environment suitable to simulation (Walters et al., 1997). Using the constructed mass balance Ecopath models of a system, ECOSIM can predict changes on the biomass of its components when the catches (fishing mortality) of one or more group is altered or simulated. The package can work out equilibrium yield (potential yield) for the concerned group by plotting equilibrium biomass for the range of F values (Kumar et al.,

2017). Several attempts were made to develop a mass balance model for the marine ecosystem of Indian Ocean with an aim to give insight into the fisheries of the region and the impact of fisheries over its components (Vivekanandan et al., 2003; Haputhantri et al., 2008; Mohamed et al., 2008; Ullah et al., 2012; Isha et al., 2018; Karim et al., 2018). The EwE with the gear decomposed catch data can be used for the estimation of equilibrium yield or potential yield (Zhang et al., 2019). The potential yield estimates can also be cross-validated with alternate methods *viz.*, primary productivity based or trophodynamic approach as done in the national estimate of potential yield for Indian fishery (DAHDF, 2011).

3. Objective 1 - PASSIVE GEO-REFERENCING OF HISTORIC FISHING DATA USING THE DISTANCE FROM THE FISHING GROUND DATA FROM CMFRI AND ITS VALIDATION

3.1. Methodology

The fishery data were collected from the various fishing fleets, i.e., Multi-day trawler (MDTN), Mechanized dolnetter (MDOL), Mechanized gillnetter (MGN), Mechanized trawler (MTN), Outboard dolnetter (OBDOL), and Outboard gillnetter (OBGN) operated from 31 fish landing centers in Gujarat. The expanse of the study area was divided into 16 zones (1.0^0 latitude X 1.5^0 longitude) for spatial comparison (20 to 24 ^{0}N and 67 to 72 ^{0}E). Overall, 13991 data points were generated across the three-year time period. The ICAR-CMFRI generates fish landing database for the marine fishery resources at State and zone levels, in addition to different gears and crafts, resources/groups/species within a limited temporal scale using a stratified multistage random sampling technique (Srinath et al., 2005). The GPS location (latitude, *lat* and longitude, *lon*) of the landing center, distance traveled by the fishing craft observed (in kilometers) and bearing (in degrees from North) were used to estimate the possible (random) fishing ground by the method referred to as 'passive geo-referencing'. The Haversine functions used for arriving at the GPS location of fishing grounds were as suggested by Van Brummelen (2013):

$$lat2 = ASIN\ (SIN(lat1) * COS\left(\frac{d}{R}\right) + COS(lat1)(SIN\left(\frac{d}{R}\right) * COS\ (\theta)$$

$$lon2 = lon1 + ATAN2(COS\left(\frac{d}{R}\right) - SIN(lat1) * SIN(lat2), SIN(\theta) * SIN\left(\frac{d}{R}\right) * COS\,(lat1)$$

Where, *lat1* and *lon1* are the initial locations of the vessel at the beginning of the fishing trip (referred as trip initiation point) in radians, d is distance traveled in km to reach fishing ground, R is the radius of the earth in km, θ is bearing in radians, *lat2* and *lon2* are the GPS coordinates of the fishing ground in radians. A survey was made among the crew on their judgment to gaze the exact distance which was later verified by GPS record of selected boats. It was observed that on an average 20% error on both sides in distance judgment was made by the respondents of the schedule. Hence, the distances by the fishers/crew were randomized setting distance +20% of the distance as an upper limit and -20% of distance as a lower limit. To generate a random number between given limits of distance and bearing. The function used in excel was:

$$randomdistance \vee bearing = lowerlimit + (upperlimit - lowerlimit) * RAND(distance)$$

The mean CPUE was compared for a significant difference between three factors *viz*., zones, gear and quarter using Analysis of Variance (ANOVA). The data on CPUE are highly variable and hence prior to doing ANOVA, the outliers in the data were removed using inter-quartile range (only middle two quartiles were kept for analysis). The sample size of the data sets used in the present study is sufficiently large (n≥30), hence the population mean was considered instead of the sample mean to define the normal distribution of data (Central Limit Theorem) (Pauly and Zeller, 2017a). The Tukey HSD post-hoc test was opted as the sample size was highly variable across different factors. Statistical analyses and graphs plotting were performed using SPSS *ver*. 21 and R 3.2.6 software packages. The ArcGIS 10.1 software was used to generate fishing intensity, abundance (CPUE) maps for different fishing crafts.

3.2. Results and Discussion

3.2.a. Craft-wise variations in catch rates

The highest catch rate (CPUE) was observed in case of MTN with a mean of 86.36 kg/hr and the Inter Quartile Range (IQR) was 63.33 kg/hr. The catch rates and IQR computed for different fleet were; OBDOL (60.71 kg/hr and 52.25 kg/hr), MDOL (59.01 kg/hr and 61.79 kg/hr), MDTN (33.15 kg/hr and 26.13 kg/hr), MGN (28.21 kg/hr and 20.63 kg/hr) and OBGN (18.88 kg/hr and 14.13 kg/hr) (Figure 2). Though MTN and MDTN refer

types of mechanized trawlers, the catch rates observed in MTN (86.36 kg/hr) is much higher than in MDTN (33.15 kg/hr). This difference is mainly due to the retention of complete harvested catch in MTN and in the case of MDTN part of the catch (low value fishes and invertebrates) is discarded (Mohamed and Zacharia, 1997). The CPUE was nearly same in MDOL and OBDOL as there is a lot of similarity in fishing operations (fixed bag nets) and fishing grounds which are much localized (Khan, 1989). Lower catch rates noticed in MGN and OBGN (gill nets) as compared to other gears as these are passive gears and the smaller non-mechanized gill nets are usually operated by small scale subsidence/traditional fishers (Libini and Khan, 2012).

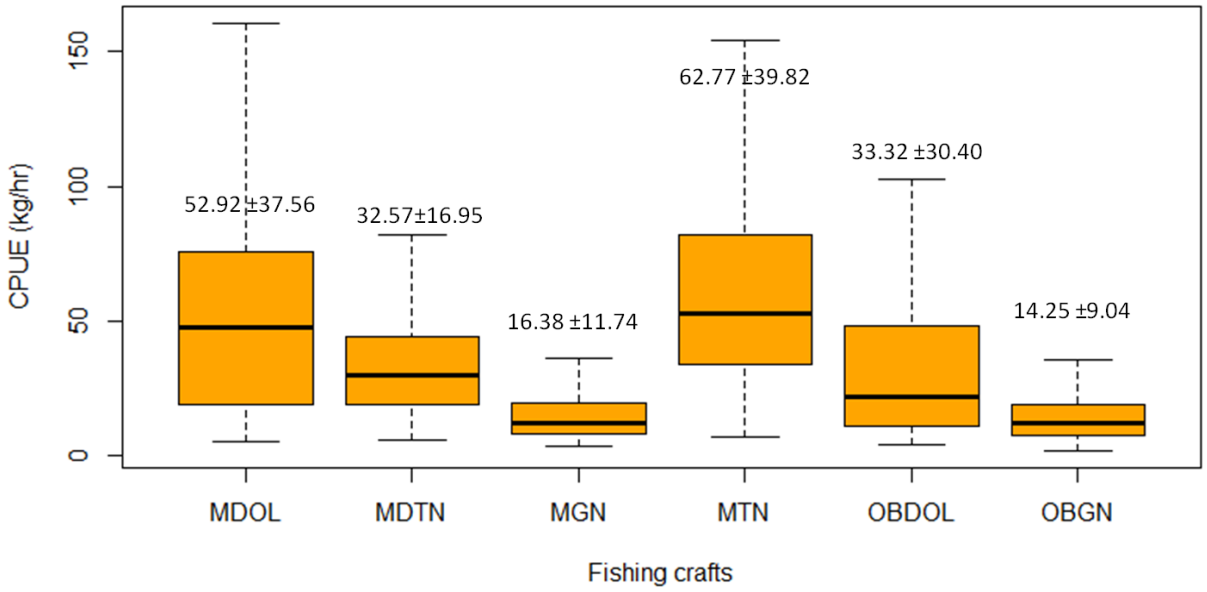


Figure 2. Box plot indicates catch rates (kg/hr) of important fishing crafts in the region

3.2.b. Fishing attributes by various crafts

Distinct variations were observed in the average depth of operation by different fishing gears. Highest variation in depth of operation was noticed for MDTN (Mean±SE, 71.30±0.98 m), followed by MGN (53.82±2.45 m), MDOL (31.37±0.33 m), MTN (26.57±0.19 m), OBGN (21.66±0.16 m) and OBDOL (16.20±0.49 m). The maximum depth of operation was noticed in MGN (>400 m), much higher than MDTN (depth of operation is <300 m). However, the average depth of operation was highest with MDTN, because of the dominance of these craft in the sector and regular distant water fishing trips (Dineshbabu et al., 2012a). Some of the MGN crafts fish in the deeper waters to exploit sharks and large pelagic resources (tuna, seerfish, barracuda, fullbeaks, large

carangids, etc.) (Koya et al., 2018a; Manojkumar et al., 2019). The operation depth of dolnets, a fixed gear, is restricted to less than 40 m. The average operation depth of MTN is less than 30 m, where fishing is restricted to a single day. The mean depth of fishing by MDOL was 30.51 m, which defined the fishing grounds were limited from shallow to moderately deep waters. Khan (1987) and Sikotaria et al. (2018) reported that the MDOL operated at 27-40 m and 40 to 60 m depths, respectively. During the study period, the longest distance traversed was recorded in MDTN (96.47±1.83 km), followed MGN (44.05±1.61 km), MDOL (26.90±0.39 km), MTN (18.06±0.19 km), OBGN (15.76±0.12 km) and OBDOL (8.85±0.34 km) (Table 1).

Table 1: Depth and distance of operation by different fishing fleet

Gear	Depth (m)			Distance (km)		
	Mean	SE mean	IQR	Mean	SE mean	IQR
MDOL	31.37	0.33	20.00	26.90	0.39	20.81
MDTN	71.30	0.98	55.00	96.47	1.83	100.48
MGN	53.82	2.45	67.00	44.05	1.61	36.37
MTN	26.57	0.19	12.00	18.06	0.19	11.85
OBDOL	16.20	0.49	10.00	8.85	0.34	5.46
OBGN	21.66	0.16	16.00	15.76	0.12	11.07

3.2.c. Temporal variations in catch rates

Highest catch rates (CPUE) of 47.84 kg/hr was noticed in the fourth quarter (October-December) and the lowest (35.87 kg/hr) was recorded in the third quarter (July-September). Moderate catch rates were observed during the Ist (40.98 kg/hr) and IInd quarters (43.26 kg/hr) (Figure 3). However, regarding the temporal dynamics, the fourth quarter is more productive with respect of catch, effort and catch rates as compared with other quarters across all the crafts, because of the perennial ecological productivity in the region ($F(3, 13387) = 22.54$, $p<0.05$) (Khan, 1989; Vase et al., 2018). This could be because of the positive impact of the fishing ban and increase in fishing effort along the shelf waters. Fishers in the region opined that fishing during the fourth quarter was restricted within the shelf area because of the prevalence of cold winds and strong currents in the open sea. In the current study, the zones falling in the coastal shelf region witnessed higher fishing effort as compared to offshore zones as both mechanized and motorized crafts operated in this region (Ghosh et al., 2009; Koya et al., 2018a). The

catchability efficiency of the fishing gear will be more or less stable, but the exertion of fishing effort and the economic drivers might influence the catch rates of the resources.

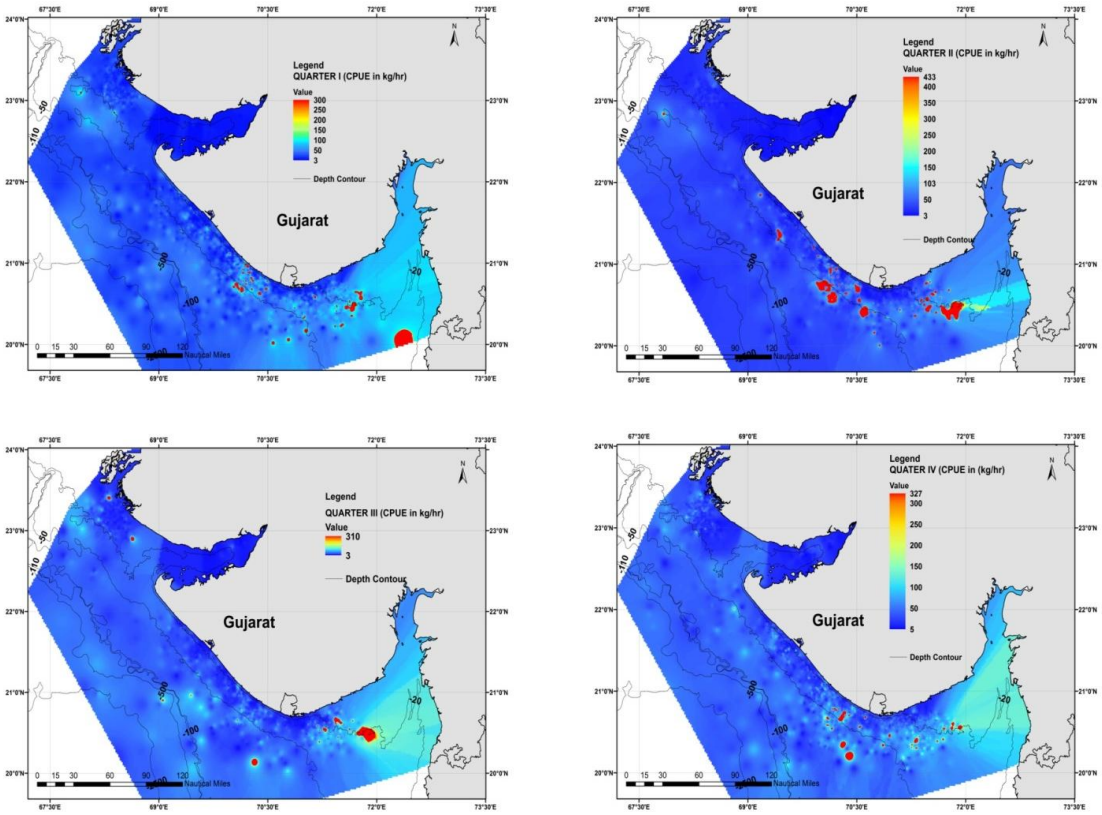


Figure 3: Temporal (quarter-wise) variations in CPUE (kg/hr) across all fishing crafts in the study region

3.2.d. Spatial variations in catch rates by selected fishing fleet

The catch rates for different fishing fleet in the studied region is provided in Figure 4. The spatial coverage of multi-day trawlers fishing is wider, which covers coastal to offshore waters in the region. The MDTN crafts operated in most of the zones, except zone X and zone XVI (outboard gillnetters were operated). The highest catch rates recorded for the zone VIII (43.44±16.44 kg/hr), followed by zones like zone IV (43.30±17.83 kg/hr), zone III (39.89±17.03 kg/hr), zone I (37.13±20.80 kg/hr), zone VII (33.35±14.81 kg/hr), zone II (31.80±18.50 kg/hr), etc . A one-way analysis of variance was performed to understand the differences in catch rates of various zones and was significant ($F(11, 1693) = 24.03$, $p<0.05$). These results indicated that, though MDTN operated in a wide geographical range, it preferred to operate on the fishing grounds in offshore zones where the fishes were abundant. The depth in the offshore zones does not

support bottom trawling and therefore mid-pelagic and pelagic trawling targeting ribbonfishes and cephalopods were prevalent (Dineshbabu et al., 2014; Kumar et al., 2019). The highest catch rates were recorded in fishing zones in the coastal shelf (zone VI (89.01 kg/hr), zone XVI (72.77 kg/hr), zone XI (70.72 kg/hr), zone XII (67.51 kg/hr), and zone II (65.31 kg/hr)). Significant variations in catch rates of various zones were observed in the region ($F(9, 2430) = 15.72$, $p<0.05$). Trawling in shelf waters yielded diverse resources, including the commercially exploited target resources, bycatch, and non-conventional groups (Zacharia et al., 2006).

The highest catch rate was recorded in zone IV (50±36.38 kg/hr), followed by zone VIII (46.73±47.14 kg/hr), zone I (35.63±19.34 kg/hr), zone XII (29.98±15.72 kg/hr), zone III (24.25±15.25 kg/hr), zone VI (23.92±16.76 kg/hr), zone VII (22.61±13.16 kg/hr), zone II (18.91±11.41 kg/hr) and zone XVI (12.28±7.84 kg/hr) by MGN craft. The spread of resources in the sea was highly dynamic and the overlap of different fishing zones was observed in the mean catch rates. The higher catch rates were recorded in moderately deeper zones than in the coastal zones (Koya et al., 2018b; Manojkumar et al., 2019). In case of OBGN, the highest catch rates recorded was for the zone XV (19.93±10.96.38 kg/hr), followed by zone III (19.29±11.94 kg/hr), zone XVI (18.24±9.15 kg/hr), zone XII (16.45±9.34 kg/hr), zone VII (13.74±8.31 kg/hr), zone VI (13.02±8.70 kg/hr), zone II (12.78±8.90 kg/hr) and zone XI (11.91±7.59 kg/hr), etc. The OBGN operated along coastal waters in the region and fished in all zones except in offshore zones (zone IV and zone VIII). ANOVA showed significant variations in catch rates between different zones ($p<0.05$).

The mechanized dolnetters do fishing in limited spatial range, mostly restricted within 60 m depth zones in the region. The MDOL crafts majorly operated from the landing centers like Jafrabad, Navabander, Rajpara, Ghogla, Jakhua (Khan, 1989). The MDOL crafts restrict fishing in the zone I, zone II, zone VI, zone VII, zone XI, zone XII, zone XV and zone XVI. The highest catch rates recorded for the zone I (81.31±36.38 kg/hr), followed by zones like zone VII (60.54±47.14 kg/hr), zone XII (48.24±19.34 kg/hr), zone XVI (46.70±24.91 kg/hr), zone II (45.53±35.72 kg/hr), zone XV (42.45±17.66 kg/hr), etc. A one-way analysis of variance was performed to understand the differences in catch rates and was significant ($F(8, 2120) = 49.44$, $p<0.05$). The

MDOL fishing in Gujarat recorded better mean catch rates in southern fishing zones, and the lower catches in the northern fishing grounds during the study period. The outboard dolnetters do fishing in limited spatial range, mostly the fishing grounds located in coastal waters. The fishing by OBDOL crafts limited with few zones like zone I, zone II, zone VI, zone VII, zone XIV, zone XV and zone XVI. The highest catch rates recorded for the zone I (83.34±33.49 kg/hr), followed by zones like, zone II (36.82±30.36 kg/hr), zone XVI (22.95±27.99 kg/hr), zone XIV (11.93±2.29 kg/hr), zone VI (9.32±3.68 kg/hr), zone XV (8.97±1.35 kg/hr), etc. ANOVA revealed a significant differences in catch rates across zones ($F(5, 319) = 13.46$, $p<0.05$). The fishing zones under the Saurashtra region recorded better catch rates than the Kutch region in the state.

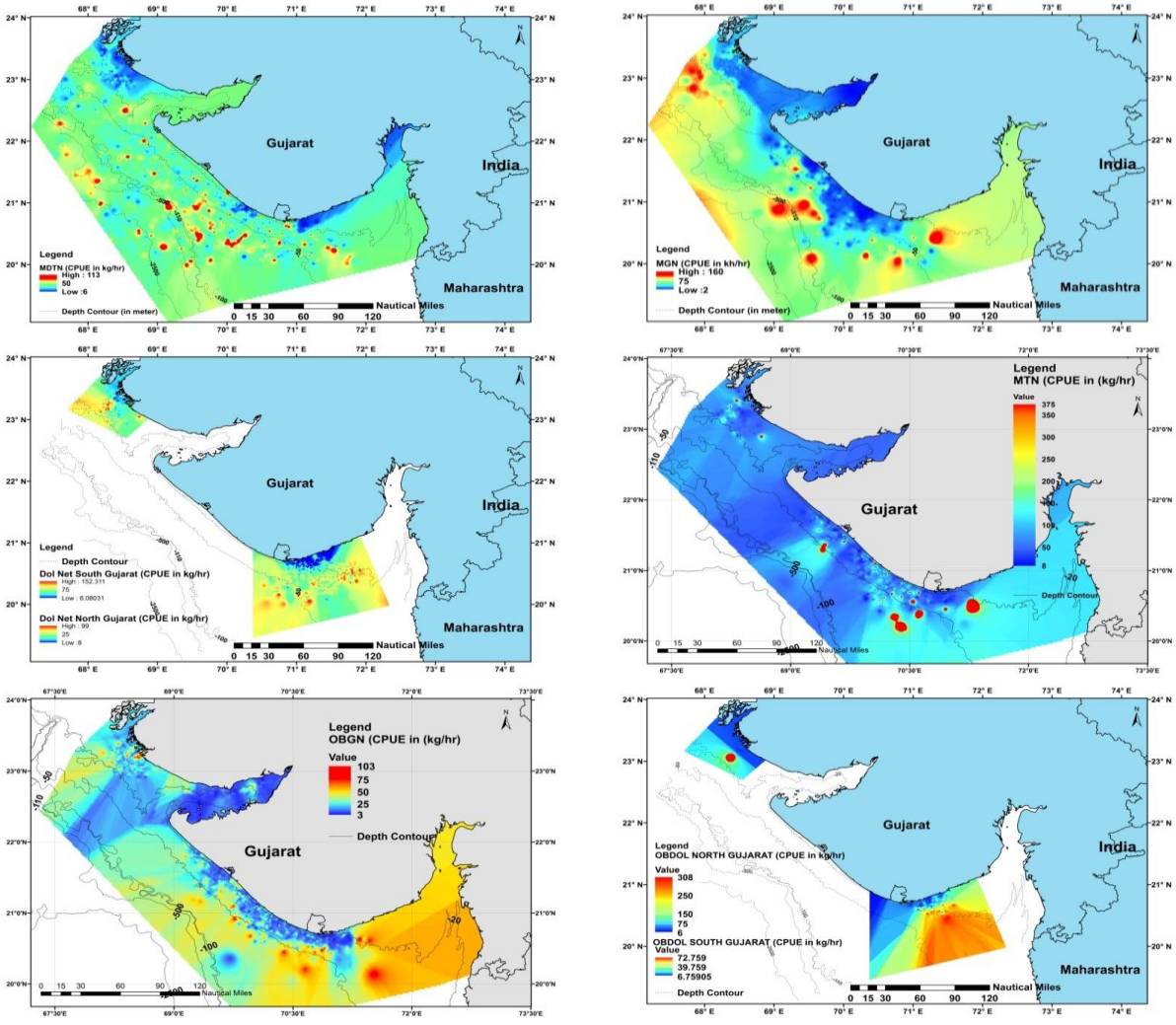


Figure 4: Spatial distribution of catch rates (CPUE, kg/hr) of MDTN, MGN, MDOL, MTN, OBGN, and OBDOL fleet

4. Objective 2 - MODELING AND ESTIMATION OF MARINE PRIMARY PRODUCTIVITY OFF GUJARAT

4.1. Methodology

The spatial and temporal variations in primary productivity (mg C m^{-2} day^{-1}) in the northern Arabian Sea (20-24 ^{0}N, 66-72 ^{0}E) during 2015 to 2017 (monthly average) was studied using the satellite VGPM model to tag productivity seasons and zones. The 8-day composite level-3 satellite data were retrieved from the OC-CCI database version 1 (Peters et al., 2019). The chlorophyll-*a* and downwelling diffuse attenuation coefficient at 490 nm data was retrieved from the SeaWiFS and MODIS. The PAR (8-days composite and level 3 data) was downloaded from the Ocean Productivity (NASA's Ocean Color Web) database (O'Malley, 2019). The euphotic depth could be computed from parameters like k_{d490} and surface chlorophyll and the minimum error model was adopted in the present study (Morel and Berthon, 1989). The Day Length (DL), a synonym of photoperiod (hr), was calculated using an astronomical algorithm as a function of latitude and a day for a year, which was retrieved from the secondary literature (Thorsen, 2019).

A total of 204 samples were analyzed from different locations during the winter monsoon (November-February), spring inter monsoon (March-May), summer monsoon (June-September), and fall inter-monsoon (October) to understand the seasonal variations in PP (DAHDF, 2011). Rough sea conditions during the peak monsoon months (June-July) prevented sampling during this period. For the present study, the *in-situ* primary production measured by the Light and Dark bottle method with 10-hour incubations for sampling stations was used. The water samples were incubated for a suitable time at controlled illumination and temperature (providing *in-situ* conditions). The water samples (300 ml) for the DO estimation were collected from just beneath the sea surface between 09:00 and 14:00 hours of the sampling day. The estimates of DO from replicates were comparable and robust (SE < 0.05) and hence found suitable for the estimation of NPP. The changes in dissolved oxygen levels in the light and dark bottles were expressed as productivity in g C/unit volume/hr and calculated as (Strickland and Parsons, 1968; Gaarder, 1927).

$$NPP = \frac{(x - z) \times 0.536}{PQ \times t} mgC/l/hr$$

Where x is O_2 of light bottle after incubation, z is O_2 of light bottle initially fixed, PQ is the photosynthetic quotient (1.25), and 't' is the number of hours of incubation (3 hrs). For the expression of productivity in m^{-3} day^{-1}, the above value shall be multiplied by 10000 (assuming 10 sunshine hours affect photosynthesis in a day).

The Vertically Generalized Production Model (VGPM) is one of the standard MODIS algorithms, developed by Behrenfeld and Falkowski (1997a, b). This model is widely known and used in WIDI PP models. The model estimates daily primary production in the euphotic layer from surface Chl-*a* concentration, PAR, day length, euphotic depth, and the optimum photosynthetic rate (P_{opt}^{B}) of phytoplankton in the water column. In algorithm calculation, the euphotic depth was estimated using K_d. The VGPM proposed by BF is:

$$IPP = 0.66125 \times P_{opt}^{B} \times \left[\frac{PAR}{(PAR + 4.1)}\right] \times Z_{eu} \times Chl - a \times D_{irr}$$

where, *IPP*, P_{opt}^{B}, *PAR*, Z_{eu}, *Chl-a*, and D_{irr} are integrated primary production (mg C m^{-2} day^{-1}), the maximum primary production per unit of chlorophyll in the vertical profile (mg C m^{-2} hr^{-1}), photosynthetically active radiation (mol quanta m^{-2} day^{-1}), depth of euphotic zone (m), and sea surface chlorophyll (mg m^{-3}), and day length (hr) respectively. The P_{opt}^{B} is expressed by BF as a 7^{th} order polynomial of temperature (T):

$$P_{opt}^{B} = -3.27 \times 10^{-8}T^{7} + 3.4132 \times 10^{-6}T^{6} - 1.348 \times 10^{-4}T^{5} + 2.462 \times 10^{-3}T^{4} - 0.0205T^{3} + 0.0617T^{2} + 0.2749T + 1.2956$$

The computed *in-situ* PP in the study region was evaluated PP measurements of five different models: two models were based on satellite data sets (VGPM and EVGPM) and three models were modified variants of VGPM (VGPM-BF, VGPM-KI, and VGPM-E). The formulation and parameterization were verified as suggested by BF and KI for the calculation of P^{B}_{opt} to estimate integrated primary production using ocean color satellite data (PAR, I), Z_{eu}, *in-situ* SST, and *in-situ* chlorophyll-*a*.

The descriptive statistics were computed for the various input variables and PP measurements estimated by five PP models. The mean absolute percentage error (MPE) was calculated for how close model predictions (P_n) are to the *in-situ* observations (O_n) (Malgorzata and Agata, 2013).

The precision indicator RMSD was used to assess the model efficiency. The root-mean-square difference (statistical error) was calculated to assess overall model performance in terms of both bias and variability in a single statistic. The RMSD assesses model skill such that models with lower values had higher efficiency (Saba et al., 2011):

$$RMSD = \left(\frac{1}{N}\sum_{i=1}^{N}\Delta\,(i)^2\right)^{1/2}$$

Where the model-data misfit in $\log_{10}$ space $\Delta(i)$ is defined as:

$$\Delta(i) = log\big(NPP_m(i)\big) - log\big(NPP_d(i)\big)$$

and $NPP_m(i)$ is modeled NPP and $NPP_d(i)$ represents in-situ data for each sample *'i'*. To assess model skill (whether a model over- or underestimated NPP), we calculated each model's bias (B) for each region where:

$$B = log(\acute{N}PP_m) - log(\acute{N}PP_d)$$

One way analysis of variance (ANOVA) was attempted to assess the significant differences between the model and *in-situ* mean PP values on temporal and spatial scales. Finally, the scatter diagrams, standard deviation (SD), Pearson's correlation coefficient, and linear regression (coefficients S & I) were considered to understand the consistency between modeled and *in-situ* PP estimates. The satellite data was level 4 processed and in NetCDF format, which was processed through the SeaDAS 7.5.1 version software (Gene, 2021).

4.2. Results and Discussion

Significant temporal variations (monthly) were observed in satellite PP data (VGPM) in the region. Highest primary productivity was observed during the winter and spring seaons, with a maximum in February (2349±231 mgC m^{-2} day^{-1}) and the minimum in June (700±13 mgC m^{-2} day^{-1}). The *in-situ* PP values showed significant interannual variations (ranges from 1938 to 4863 mgC m^{-2} day^{-1}), and the maximum was observed during the winter (3430 mgC m^{-2} day^{-1}) and the lowest in summer monsoon (3129 mgC m^{-2} day^{-1}) (Table 2). The temporal variations in PP were principally influenced by environmental factors like nutrients, SST, light radiation, winter convective mixing by winds, upwelling, etc (IOCCG, 2000; Shang et al., 2010). However, the study region is located in the tropics, where solar radiation (PAR 28.48 to 56.29 Ein m^{-2} day^{-1}), light

intensity (average day length is 11.47hr), and temperature (22.50 to 28.20^{0}C) are high throughout the year (Figure 5) and these parameters can act as limiting factors for the intensity of PP (Tan and Shi, 2009). The wide continental shelf, the existence of gulf ecosystems, winter convective mixing, and coastal upwelling are the key factors for the high productivity in the region (Tripathy et al., 2012; Vase et al., 2018). The satellite-derived of SST for the calculation of P^B_{opt}, likewise Chl-*a* and k_d to compute Z_{eu} for coastal areas yield highly erroneous PP values. The linear regression depicted that the input variables (Chl-*a*, PAR, Z_{eu}, DL) together explained 48.68% variation in the PP. Chlorophyll-*a* (p=0.000) significantly influenced the variability of PP, followed by DL (p=0.003), PAR (p=0.008) and Z_{eu} (p=0.021) and also other factors like nutrients, monsoon cycles, upwelling, and coastal currents. The uncertainty attributed to the input variables in the region is lower than the globally suggested values (IOCCG, 2000; Saba et al., 2011).

Table 2: Descriptive statistics of primary productivity (mgC m^{-2} day^{-1}) measured by *in-situ* and various models in the region (N=204)

Type of dataset	Mean	SD	Minimum	Maximum	Q1	Q3	IQR	CV
$PP_{in\text{-}situ}$	3372.1	665.1	1937.8	4863.0	2870.9	3903.0	1032.1	19.72
EVGPM	1645.9	602.0	659.9	3614.7	1277.0	2030.4	753.4	36.6
VGPM	1183.6	514.4	312.6	2669.2	790.2	1454.7	664.5	43.5
VGPM-KI	7099.9	1295.2	4545.9	11029.0	6160.3	7882.6	1722.3	18.2
VGPM-BF	8799.0	1779.0	5355.0	14369.0	7373.0	10060.0	2687.0	20.2
VGPM-E	5181.5	1130.0	2838.1	8713.1	4410.7	5706.1	1295.4	21.8

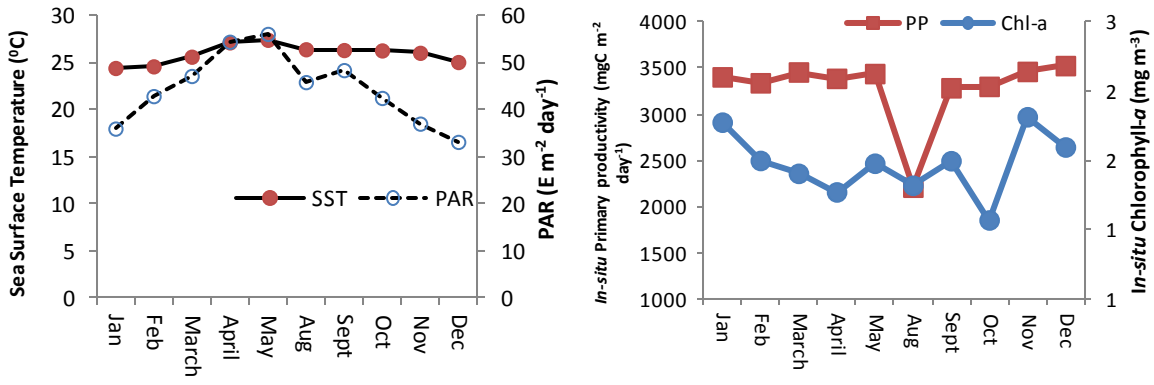


Figure 5. Monthly average variations of mean (a) SST and PAR, (b) Chl-*a* and PP

The better variation was observed in the modified models than the satellite models, because of the correction of *in-situ* input variables in the algorithms. Incorporation of the input variables (*in-situ* Chl-*a* and SST) in the global remote sensing algorithms (VGPM and EVGPM) significantly overestimated PP in the Arabian Sea due to the eutrophic nature (mean Chl-*a* is 1.422±0.45 mg m^{-3}), higher SST (25.74±1.26 ^{0}C), DL (11.47±0.72 hr) and PAR (43.24±7.37 Ein m^{-2} day^{-1}) (Raman, 2013). The correlation (r) explained 0.421 to 0.619 with the *in-situ* PP measurements across all the models. The model estimates showed a significant positive correlation with measured PP, VGPM-KI (r=0.619, p<0.05), VGPM-BF (r=0.581, p<0.05), and VGPM-E (r=0.565, p<0.05). However, a moderately significant positive correlation noticed in the case of satellite VGPM (r=0.421) and EVGPM (r=0.500) (Figure 6). The PP estimates by VGPM-KI model explained the highest variance of 38.3% in comparison with measured PP, but the lower variance was noticed with satellite PP data (25% variance by EVGPM and 19% variance with VGPM). The satellite-derived PP accounted for 50 to 80% of the variance in comparison with the *in-situ* PP, the rate of variance depended on the input parameters used in the model (Balch, *et al.,* 1992; Berthon and Morel, 1992). The specific regional parameterization requires the development of various models to estimate PP accurately, to address the atypical optical and photo-physiological characteristics from region to region (IOCCG, 2000).

Table 3: Validation statistics for each model in the region, i.e., correlation coefficient (r), log RMSD, log Bias, *S* is the slope, *I* is the intercept of the linear regression coefficients, and R^2 is the coefficient of the determination.

***In-situ* vs**	**r**	**logBias**	**Log RMSD**	**ME**	**Slope (S)**	**Intercept (I)**	**R^2**	**MPE**
EVGPM	0.500	0.14	0.02	-4.19	0.453	116.77	0.251	46.36
VGPM	0.421	-0.02	0.02	-4.05	0.334	56.34	0.187	5.26
VGPM-KI	0.583	0.80	0.32	-81.41	1.207	3045	0.383	542.53
VGPM-BF	0.548	0.89	0.40	-101.29	1.553	3580	0.338	659.55
VGPM-E	0.531	0.66	0.22	-55.62	0.963	1947	0.319	367.97

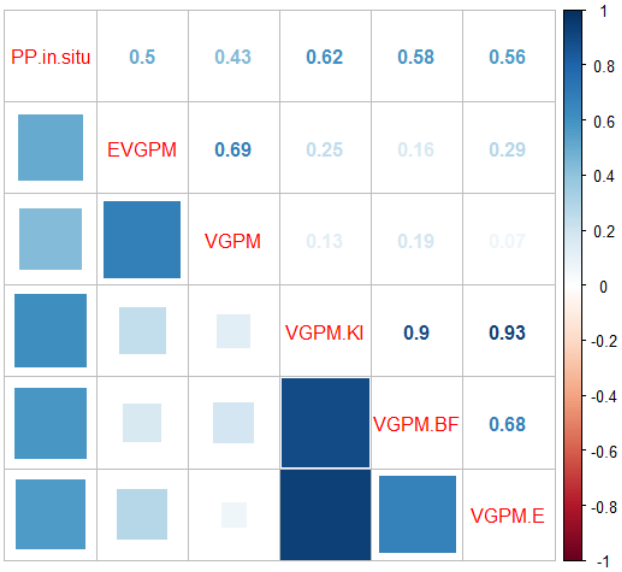


Figure 6: Correlation of PP measurements (mgC m^{-2} day^{-1}) between *in-situ* and various models in the region

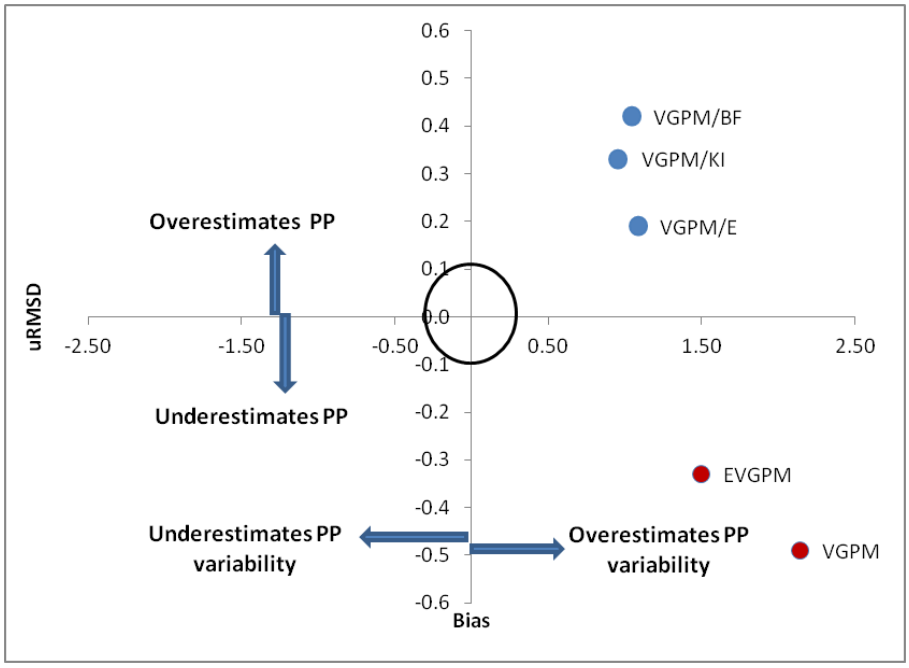
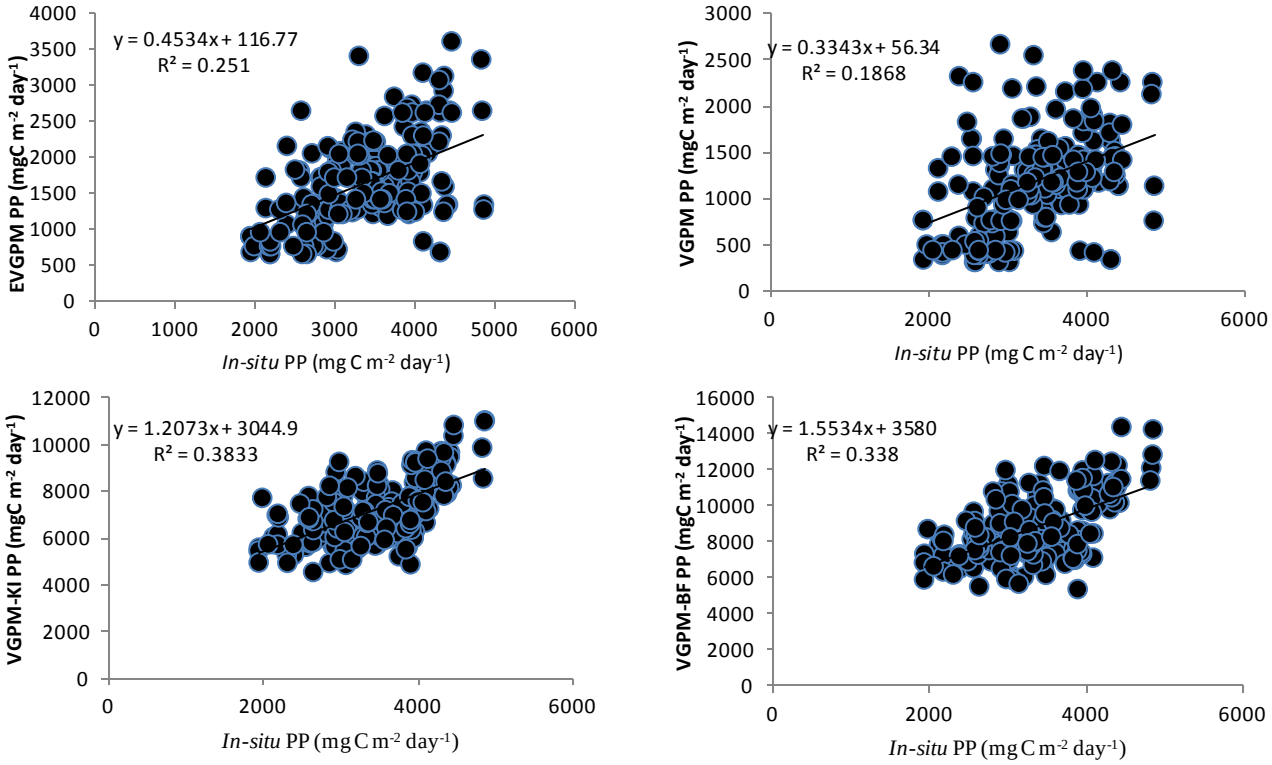


Figure 7: The ability of the different models represented in the Target diagram. The red symbols represent satellite PP estimates and the blue symbols represent model PP values. The solid circle is the standard deviation of the observed data (σ_d) in the region.

The average RMSD among the five models applied in the region was 0.22, which is better performed than the earlier discussed models and matching with previous Arabian Sea values. The log RMSD was not consistent among five different models (ranged from 0.02 to 0.40) in the study region. The lower log RMSD was observed for VGPM and

EVGPM models at 0.02. Still, a significantly better skill performance was observed for the modified VGPM variants, i.e., VGPM-E (0.22), VGPM-KI (0.32), and VGPM-BF (0.40) (Table 3). The average RMSD estimates among 12 ocean color models in the Northeast Atlantic Ocean region was 0.31 (Campbell et al., 2002) and 0.14 (Saba et al., 2010), the improvement of the model might be due to the higher sample size. The mean RMSD of 21 ocean color models tested in the tropical Pacific was 0.29 (Friedrichs et al., 2009), which is similar in skill to the Arabian Sea (0.22) and North Pacific Ocean (0.26). The RMSD values estimated in the present study is not deviate from earlier studies in the same and other contemporary regions (Saba et al., 2010, Friedrichs et al., 2009), depicting the better performance of a models in the region. In the northern Arabian Sea, VGPM-KI and VGPM-E performed better than the other models (Figure 7). The PP in the region is mainly influenced by biogeochemical cycles and ocean processes like coastal upwelling and winter convection by winds, which are the primary reasons for the perennial productivity. The scatter plots depicted that the PP estimates were overestimated in the region across the different models (Figure 8).


y = 0.4534x + 116.77
R² = 0.251
EVGPM PP (mgC m-2 day-1)
In-situ PP (mg C m-2 day-1)
y = 0.3343x + 56.34
R² = 0.1868
VGPM PP (mgC m-2 day-1)
In-situ PP (mg C m-2 day-1)
y = 1.2073x + 3044.9
R² = 0.3833
VGPM-KI PP (mgC m-2 day-1)
In-situ PP (mg C m-2 day-1)
y = 1.5534x + 3580
R² = 0.338
VGPM-BF PP (mgC m-2 day-1)
In-situ PP (mg C m-2 day-1)

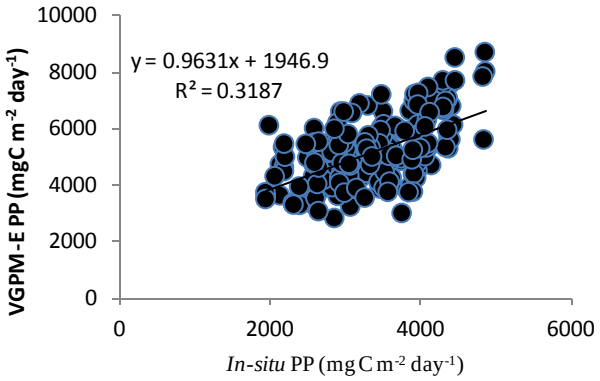


Figure 8: Scatter plots of log satellite, model and *in-situ* PP (mgC m^{-2} day^{-1}) in the northern Arabian Sea (N=204) (five models are VGPM, EVGPM, VGPM-KI, VGPM-BF, and VGPM-E)

5. Objective 3 - MODELING AND ESTIMATION OF MARINE FISH YIELD OFF GUJARAT

5.1. Methodology

The time-series catch and standardized effort data inputs in the surplus production model. The fishery resources landed in the State were categorized into 25 groups for the present study. The gear wise catch and effort data for selected groups for the period 1994-2018 was sourced from the National Marine Living Resources Data Centre (NMLRDC) of the ICAR-Central Marine Fisheries Research Institute, Kochi. The catch per unit effort (CPUE) was calculated from catch and fishing effort data. A resource group-specific standardized effort would be a better input than the pooled effort due to the multi-species and multi-gear fishery. The basic surplus production model (Schaefer, 1954) was used for calculation of biomass, fishing mortality, and yield in the simulation. The model function is given as:

$$\frac{dB_t}{dt} = rB_t\left(1 - \frac{B_t}{K}\right) - F_t B_t$$

Where B_t is the biomass at time t (year), r is the intrinsic rate of increase of the stock, K is the carrying capacity, and F_t is the fishing mortality rate. The recursive expressions for calculating biomass and yield as given by Prager (1994), based on the model parameters, initial biomass B_0, carrying capacity K, intrinsic growth rate r, and catchability coefficient q, were followed in this study.

$$MSY = \frac{Kr}{4}; B_{MSY} = \frac{K}{2}; F_{MSY} = \frac{r}{2}; f_{MSY} = \frac{r}{2q}$$

The Schaefer model parameters were estimated using the *prod_mod_ts* module under the TropFishR package for fish stock assessment in R.

The ECOPATH model was attempted in addition to surplus production model to compute potential yield, which is basically a mass balance routine for an ecosystem originally based on mass balance function given by Polovina (1984):

$$B_i * (P/B)_i * EE_i = \sum_i (Q/B)_i * DC_{ij} * B_j + C_i + BA_i + NM_i$$

Where, B_i & B_j are the biomasses of the species i and its consumer j, $(P/B)_i$ is the production to biomass ratio for i, EE_i is the ecotrophic efficiency of i, C_i is the catch or fishing mortality for the species/group i, $(Q/B)_j$ is the consumption to biomass ratio for the group j, BA_i is the biomass accumulation for each unit time and NM_i is the net migrated biomass of i. In addition, the information on catch rate, net migration, biomass accumulation rate, assimilation rate, and diet composition are to be provided for each group (Christensen and Pauly, 1992). In the present study 45 functional groups including detritus were used for model construction. The biomass of primary producer (phytoplankton) is a must input in the model as it forms the base of the food web. The *in-situ* computed primary productivity was used as input in the Ecopath model for phytoplankton. The input for detritus biomass was based on estimates using Pauly's empirical formula (Pauly et al., 1993):

$$logD = 0.954logPP + 0.863logE - 2.41$$

Where D is the detrital biomass, PP is the primary production and E is the euphotic layer depth.

The biomasses of other functional groups were estimated from the catch rates of the commercial fisheries and experimental trawling. The values of Z (total mortality) estimated for the most representative species of each group (weighted average where more than one species contributes significantly to the group) a proxy for the production/biomass (P/B). The consumption/biomass was estimated using the following an empirical formula of Pauly *et al.,* (1993):

$$log\frac{Q}{B} = 7.964 - 0.204logW_{inf} - 1.965T + 0.083A + 0.532h + 0.398d$$

Where W_{inf} is the asymptotic weight of the species, T is the mean annual habitat temperature, A is the aspect ratio of the caudal fin and are the binary variables for the

food consumed (0 for carnivores and 1 for herbivore and detritivore). The diet composition of all the functional groups was computed and provided in the form of a diet matrix. The details of the functional group, Biomass (B), Production/Biomass (P/B), Consumption/Biomass (Q/B), EE, and Production/Consumption (P/Q) as output from the model are provided in Table 4. The linear equations of Ecopath models can be converted to differential equations to generate a dynamic mass balance scenario which can be subjected to a simulation (Walters, *et al.*, 1997). The equations are derived from the ECOPATH master equation can be written as:

$$\frac{dB_i}{dt} = g_i \sum_j C_{ji} - \sum_j C_{ji} + I_i - (M_i + F_i + e_i)B_i$$

Where dB_i/dt represents the growth rate during the time interval dt of group (i) in terms of its biomass, B_i, g_i is the net growth efficiency (production/consumption ratio), M_i the non-predation natural mortality rate, F_i is the fishing mortality rate, e_i is emigration rate, I_i is the immigration rate, e_i is the emigration rate. The F_{MSY} and relative catch corresponding to them were estimated using the F_{MSY} module in the Ecosim to arrive potential yield of different functional groups (Kumar et al., 2017). Most of the settings were kept by default while setting up an Ecosim scenario and the vulnerabilities were scaled to the trophic level for each functional group. The F_{MSY} and relative catch corresponding to them were estimated for each group keeping the biomass of the other groups stationary.

Table 4: Basic input/output of the Ecopath model for Gujarat fishery ecosystem

Sr. No.	Functional Group	TL	Biomass (t/km^2)	P/B ($year^{-1}$)	Q/B ($year^{-1}$)	EE	P/Q ($year^{-1}$)
1	Billfishes	4.439	0.030	0.470	4.700	0.333	0.100
2	Oceanic tunas	4.072	0.053	1.370	11.640	0.277	0.118
3	Neritic tunas	3.624	0.343	1.960	9.600	0.449	0.204
4	Sharks	3.650	0.140	2.400	8.000	0.284	0.300
5	Eels	3.250	0.063	0.831	4.800	0.924	0.173
6	Ribbonfish	3.517	1.363	0.900	3.200	0.803	0.281
7	Wolfherring	3.815	0.076	1.500	5.300	0.989	0.283
8	Bombayduck	3.608	0.974	3.350	16.500	0.776	0.203
9	Lizardfishes	3.785	0.209	1.900	7.000	0.952	0.271
10	Barracudas	3.848	0.074	0.810	4.700	0.410	0.172
11	Half & full beaks	3.508	0.079	1.980	6.700	0.908	0.296

12	Halibut	3.351	0.017	2.250	9.200	0.149	0.245
13	Rays	3.099	0.021	1.980	12.800	0.517	0.155
14	Skates	3.189	0.021	1.350	11.500	0.454	0.117
15	Rockcods	3.120	0.099	2.710	13.900	0.960	0.195
16	Seer fishes	3.689	0.159	1.900	7.400	0.315	0.257
17	Threadfin breams	3.270	0.430	3.090	14.100	0.975	0.219
18	Other perches	3.226	0.306	2.800	9.300	0.827	0.301
19	Croakers	3.123	0.864	3.300	15.200	0.807	0.217
20	Threadfins	3.577	0.080	1.400	4.900	0.983	0.286
21	Carangids	3.448	0.721	3.100	10.300	0.965	0.301
22	Cephalopods	3.219	0.956	3.300	23.830	0.948	0.138
23	Big Jawed Jumper	3.312	0.012	2.910	9.700	0.986	0.300
24	Small mesopelagics	2.773	2.519	3.890	13.100	0.800	0.297
25	Soles	2.499	0.120	2.100	8.600	0.840	0.244
26	Catfishes	3.175	0.422	1.620	7.300	0.248	0.222
27	Goatfishes	3.213	0.054	2.610	11.100	0.925	0.235
28	Lobsters	2.597	0.013	1.890	14.500	0.877	0.130
29	Crabs	2.308	0.410	4.360	14.500	0.959	0.301
30	Stomatopods	2.577	0.304	1.980	14.500	0.988	0.137
31	Silver bellies	2.873	0.051	5.920	29.400	0.886	0.201
32	Other clupeids	3.163	0.621	5.600	18.600	0.980	0.301
33	Flying fishes	3.016	0.061	4.500	15.200	0.917	0.296
34	Indian mackerel	2.951	0.060	3.020	10.300	0.973	0.293
35	Mullets	2.123	0.075	1.604	12.280	0.988	0.131
36	Pomfrets	2.703	0.154	2.240	7.600	0.610	0.295
37	Penaeid prawns	2.281	0.471	5.650	19.200	0.961	0.294
38	Other sardines	2.723	0.500	7.070	40.000	0.883	0.177
39	Shads	2.034	0.091	2.600	20.700	0.869	0.126
40	Oil sardine	2.176	0.081	5.190	40.100	0.877	0.129
41	Non-penaeids	2.359	2.628	13.000	26.400	0.950	0.492
42	Heterobenthos	2.053	5.800	9.000	60.000	0.799	0.150
43	Zooplankton	2.048	15.000	21.760	119.000	0.480	0.183
44	Phytoplankton	1.000	45.000	44.138		0.900	
45	Detritus	1.000	15.500			0.389	

5.2. Results and Discussion

The Potential Yield, PY/Maximum Sustainable Yield, MSY for each of the resource group was calculated by two suplus production models i.e., Bayesian Surplus Model, BSM and Catch-MSY Model, CMSY. The pooled PY across selected resource

groups were estimated at 9.05 lakh t by BSM model and 8.73 lakh t by CMSY model. The MSY values computed using CMSY model for the important resources like, clupeoids (0.83 lakh t), Bombayduck (0.70 lakh t), carangids (0.26 lakh t), ribbonfish (1.33 lakh t), seerfish (0.11 lakh t), tuna (0.12 lakh t), Elasmobranchs (0.28 lakh t), catfish (0.31 lakh t), croaker (0.74 lakh t), pomfret (0.11 lakh t), perches (0.76 lakh t), crustaceans (1.98 lakh t), and cephalopods (0.60 lakh t). The estimated MSY values were better for the remaining finfish, crustacean and cephalopod resources. The recent catch of 7.49 lakh tonnes (2019) is below the estimated potential yield computed by BSM and CMSY models, which offering further scope to increase fishing effort to harvest the underexploited resources (CMFRI, 2020). Several analytical comparisons of results obtained from the CMSY method and other stock assessment approaches were performed to test the robustness and reliability of the CMSY method (Froese et al., 2018). However, the increased fishing effort is to be limited to production of resource-specific fisheries. The conventional resource like the bombayduck was fished marginally over the potential yield. With the emergence of multi-day fishing encouraged by the Union Government for deep-sea long lining (in the form of subsidy scheme for conversion to longliners) for the exploitation of underutilized oceanic fisheries to enhance the production (DAHDF, 2018).

The mass balance routine of the EwE tool computed EE and P/Q for each of the functional groups. Sometimes, the initial EE was found to be over 1, which is not a workable value to mass balance the ecosystem. The balancing was done with minor adjustments in the diet matrix of the different functional groups. The balancing was done following guidelines laid by Heymans et al. (2016). The result of balancing is reflected in the set of graphs referred to as pre-balance diagnostics, which were assessed for sufficiency of the balancing procedure. The flow of matter (biomass) among the different functional groups is depicted in an ecopath flow diagram having phytoplankton and detritus at the base and other consumers at a higher level in accordance with estimated trophic level (Figure 9). The most important feature to test an ecosystem model is the Ecotrophic Efficiency, EE (Christensen, *et al.,* 2005). The EE is nothing but the proportion of the production consumed by predators or exported. The EE values varied between 0.149 to 0.989. The values closer to zero showed that the group is apparently

less consumed by any other group in the system. The values approaching unity shows that the group was heavily preyed or fished. Several of the groups recorded the EE value of more than 0.9 indicative of high fishing or predator pressure.

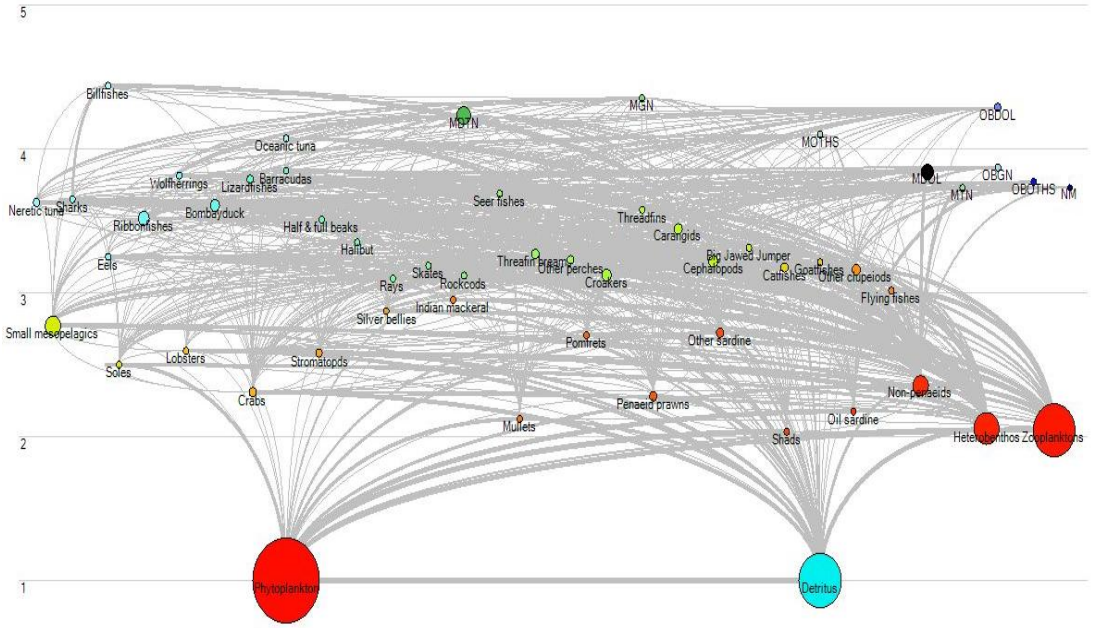


Figure 9: Flowchart of trophic interaction in the marine ecosystem of Gujarat

The system statistics for the Gujarat fishery ecosystem (Table 5) provide a key sign of the state of the marine ecosystem in terms of production, efficiency and maturity. Total system throughput is the sum of all flows in a system expressed in t km^{-2} $year^{-1}$. Total system throughput represents the 'size of the entire system in terms of flow' (Ulanowicz, 1986). The total system throughput estimated for the Arabian Sea ecosystem of Gujarat was 5237 t km^{-2} $year^{-1}$, which is consistent with tropical marine ecosystems with high turnover. The fishery in the Arabian Sea ecosystem of Gujarat had a mean trophic level of 3.08, with the minimum being 1 (phytoplankton & detritus) and a maximum of 4.439 (billfishes). The gross efficiency value will be higher for systems with a fishery harvesting fish low in the food chain than for systems whose fisheries concentrate on apex predators. It is much lower than 1.0. For the Gujarat model, the value obtained was 0.002 (much higher than the weighted global average is about 0.0002) showing a fishery harvesting fishes low in the food chain. System production will be large in immature systems and close to zero in mature ones. The value of 532.54 t km^{-2}

year^{-1} got for the Arabian Sea ecosystem of Gujarat again affirms it as the developing ecosystem.

Table 5: System statistics of Gujarat marine ecosystem

Parameter	**Value**
Sum of all consumption (t km^{-2} yr^{-1})	2386.13
Sum of all exports (t km^{-2} yr^{-1})	532.54
Sum of all respiratory flows (t km^{-2} yr^{-1})	1453.68
Sum of all flows into detritus (t km^{-2} yr^{-1})	864.22
Total system throughput (t km^{-2} yr^{-1})	5236.58
Sum of all production (t km^{-2} yr^{-1})	2441.45
Mean trophic level of the catch	3.08
Gross efficiency (catch/net p.p.)	0.002
Calculated total net primary production (t km^{-2} yr^{-1})	1986.22
Total primary production/total respiration	1.37
Net system production (t km^{-2} yr^{-1})	532.54
Total primary production/total biomass	24.36
Total biomass/total throughput (t km^{-2} yr^{-1})	0.016
Total biomass (excluding detritus) (t km^{-2})	81.53
Total catch (t km^{-2} yr^{-1})	4.08
Connectance Index	0.35
System Omnivory Index	0.24
Throughput cycled (including detritus) (t km^{-2} yr^{-1})	211.40
Ascendency	35.65
Overhead	64.35
Finn's cycling index	4.04
Finn's mean path length	2.64

The system omnivory index is a measure of how the feeding interactions are distributed between trophic levels. For the Arabian Sea ecosystem of Gujarat, an omnivory index value of 0.241 was obtained. The 'cycling index' developed by Finn (1976), is expressed here as a percentage and was estimated as 4.037% of the Arabian Sea ecosystem. The system overhead was approximately 64.35% and indicated that the

Arabian Sea ecosystem of Gujarat has significant strength in reserve and can either be resistant or resilient to perturbations with the capability to bounce back quickly to original levels. The MSY and F_{MSY} were computed using the F_{MSY} molecule in Ecosim for the Bombayduck fishery as a model output (Figure 10). The output (MSY) is presented in Table 6 and compared with the estimated MSY by the BSM and CMSY models. The MSY estimates of Ecosim, BSM and CMSY models were comparable for the many resource groups. The MSY estimated using EwE model was 11.70 lakh t, but estimates were low for the BSM and CMSY models as 9.05 lakh t and 8.73 lakh t, respecctively. The potential yield estimates for most of the fishery groups were matching between different approaches, but the wide disparity was noticed with crustaceans especially non-penaeid prawns (2.15 lakh t), and other finfish like bombayduck (0.65 lakh t), perches (0.30 lakh t), clupeids (0.24 lakh t), etc. The above-mentioned fishery resources belongs to the lower trophic levels and with higher ecotrophic efficiency. Increased effort to exploitat such resources may not affect sustainability because of the fast growth rate and short time regeneration of the fishery. The study suggests that the harvest limit can be set at potential yield estimated by the EwE model for the different fishery functional groups of Gujarat fishery resources.

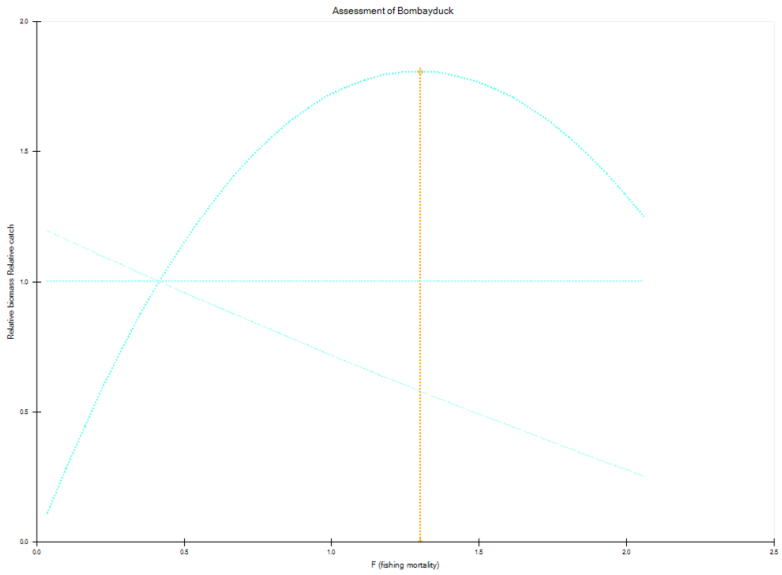


Figure 10. A typical output of F_{MSY} (Bombayduck) routine of Ecosim module in EwE

Table 6: Comparison of the MSY computed from three models, i.e., EwE, BSM, and CMSY

Fishery resources	MSY_EwE	MSY_BSM	MSY_CMSY
Billfishes	1264	480	741
Tuna	14060	17247	12210
Elasmobranchs	11273	27020	28300
Eels	4640	9883	3760
Ribbonfishes	141784	149878	133000
Clupeids	64125	56327	83211
Bombayduck	135131	68587	70200
Lizardfishes	13579	17751	18700
Barracudas	4016	1709	3290
Half & full beaks	1147	232	445
Perches	117898	61663	75817
Seer fishes	9681	17521	11290
Croakers	60892	83948	74500
Threadfins	4590	7391	5010
Carangids	29247	23975	25810
Big Jawed Jumper	791	2642	1680
Soles	14155	12636	14990
Catfishes	27582	44465	30600
Silver bellies	764	3737	928
Flying fishes	349	217	65
Indian mackerel	10845	5715	6170
Mullets	4178	2946	2520
Pomfrets	9219	13833	11181
Crustaceans	421786	200316	198820
Cephalopods	68176	74997	60100
Total	**1171172**	**905115**	**873338**

6. Summary and Conclusion

- The present work gives a comprehensive view of the marine fishing of Gujarat State in terms of depth of operation, high fishing intensity zones, and variations in fishery abundance on a spatial and temporal scale. The highest catch rate (CPUE) was observed in case of MTN with a mean of 86.36 kg/hr, followed by OBDOL (60.71 kg/hr), MDOL (59.01 kg/hr), MDTN (33.15 kg/hr), MGN (28.21 kg/hr)

and OBGN (18.88 kg/hr). Though MTN and MDTN refer types of mechanized trawlers, the catch rates observed in MTN is much higher than in MDTN due to the retention of complete harvested catch in MTN and in the case of MDTN part of the catch (low value fishes and invertebrates) is discarded. The CPUE was nearly same in MDOL and OBDOL as there is a lot of similarity in fishing operations and grounds (fixed bag nets). Lower catch rates noticed in gillnet fleet as compared to other fleet because of the operation of passive gears. The smaller non-mechanized gillnetters are usually operated by small scale subsidence/traditional fishers along the Gujarat.

- The dolnet fishery is highly localized and has not expanded spatially (both in-depth and distance) from the landing centers due to the fixed nature of the gear and its operation being based on the current movement and tidal amplitude. The mean distance of fishing by mechanized and motorized dolnetters was 26.02 km and 7.45 km, respectively. The gillnet fishery was dominated by motorized crafts, a few mechanized crafts and traditional boats. The mean distance and depth of fishing by motorized gillnetters was 15.04 km and 20.83 m. The mechanized gillnetters (MGN) deploy large meshed gear, go to distant and deeper fishing grounds and preferably target the higher trophic fishes including tuna, billfishes, large carangids, sharks, barracuda, and seer fish. In case of MGN the mean depth and distance of fishing from the landing center was 43.99 m and 36.62 km, repectively.
- The mean distance and depth of fishing by MTN fleet was 17.65 km and 26.48 m, respectively. Fishing by MTN in the region is usually for a single day with fishing being performed in the coastal shelf waters at less than 100 m depth. The mechanized fishing in the region was mainly by MDTN fleet. These crafts exploit the resources from faraway and deeper fishing grounds and mainly targeted perches, cephalopods, ribbonfishes, lizardfishes, catfishes, croakers, etc. The average distance and depth of fishing by MDTN fleet in the study region was recorded at 97.41 km and 71.56 m, respectively. The depth of operation was unlike earlier reports, it could be due to the emergence of mid-pelagic trawling in the region mostly to exploit ribbonfishes, cephalopods, threadfin breams, etc.

- The highest CPUE (47.84 kg/hr) was observed during the fourth quarter (October-December) and the lowest (35.87 kg/hr) during the third quarter (July-September). Optimum catch rates were obtained during the I^{st} (40.98 kg/hr) and II^{nd} quarters (43.26 kg/hr). The higher catch during the fourth quarter was corroborated with more fishing effort and the lower abundance was recorded in the third quarter with less fishing effort due to the fishing ban during that period. The catch rates were highly skewed depending on the extent of fishing effort and the economic drivers.
- The catch rates between the different fishing zones across various fishing crafts in the region vary. The catch rates in the different zones ranged from 8.80 kg/hr (zone X) to 94.38 kg/hr (zone I). The maximum catch rate was recorded in the zone I (94.38 ±63.52 kg/hr), followed by zone II (52.15±63.68 kg/hr), zone VIII (49.80±45.11 kg/hr), zone IV (49.07±23.82 kg/hr), zone XII (43.79±75.26 kg/hr), and zone III (40.53±28.36 kg/hr), etc. The results revealed that high catch rates were recorded from the coastal fishing zones than the offshore zones.
- The catch composition data of different fishery resources in the fishing ground was generated to get a better idea of the spatial and temporal abundance of the resources off Gujarat Coast. This data was used to comprehend the migration patterns and impact of environmental parameters on the resources. It was helpful as an information knowledge tool which could be used for security surveillance by monitoring agencies like the Navy, the Indian Coast Guard and the Marine Police. Further, the information generated through this work will play a pivotal role while formulating Marine Spatial Plans (MSPs), Marine Protected Areas (MPAs), coastal and offshore developmen plans.
- The variability (monthly & seasonal) in primary productivity by VGPM satellite data set was significant in the northeastern Arabian Sea (20-24 ^{0}N, 66-72 ^{0}E); where it is majorly influenced by the oceanic-climatic parameters like sea surface temperature, light intensity and radiation which are higher than the global average. The *in-situ* primary productivity observed in the region was significantly higher (mean of 3372.1±665.1 mgC m^{-2} day^{-1}) when compared with other contemporary regions. This could be due to the efficient mixing of nutrients by

convection winds during winter, coastal upwelling in monsoon season and also the wider continental shelf. The *in-situ* PP values indicated significant seasonal variations, the maximum was in December (3689.2 mgC m^{-2} day^{-1}) and the minimum recorded during August (2207.7 mgC m^{-2} day^{-1}).

- The satellite data underestimated PP as compared to the measured PP values, inferring that averaging of input parameters (SST, PAR, DL, Chl-*a*, Z_{eu}) at a global level across the ecosystems (polar to tropical and coastal to deep ocean) by satellite equations resulted in lower PP values. The input parameters explained over 45.10% of the variability in the measured PP, significantly by Chl-*a*, SST, PAR, etc. The modified models (with regional parameterization) performed better than the global satellite algorithms (VGPM and EVGPM) in the region.
- The model performance (log RMSD and log Bias) and efficiency values by the modified models in the region were better than the previous research findings. Across the five models the RMSD was ranges from 0.02 to 0.40 in the study region, which was better in comparison with the gobal models. The log bias values indicated that the regional models overestimates PP (VGPM-E is 0.66; VGPM-KI is 0.80; and VGPM-BF is 0.89) than the satellite models (VGPM is -0.02, and EVGPM is 0.14). The modified models showed a fair correlation ($r=0.565$ to 0.619) and regression ($R^2=0.319$ to 0.383) than the satellite algorithms in the region ($R^2=0.187$ to 0.251).
- The Potential Yield/MSY was estimated by three modeling approaches, i.e., BSM, CMSY, and EwE, and the values were mostly comparable for the commercially exploited fishery resources. The first two models were based on the catch and fishing effort, but the third model was based on mass-balanced ecosystem principles. The pooled MSY estimates made for different functional groups by using EwE was 11.70 lakh t, but estimates were lower for the BSM (9.05 lakh t) and CMSY models (8.73 lakh t). The significant difference in the potential yield between the three approaches was noticed mainly in non-penaeid prawns, perches, clupeids and bombayduck functional groups.
- The study has showed that the estimated potential yield (8.73 lak t to 11.70 lakh t) is comparatively higher than the present catch (catch of 7.49 lakh t in 2019) and

there is scope to increase the exploitation of the underutilized resources in an efficient and sustainable manner in the region. This is could be achieved by reducing the fishing effort in the continental shelf, extending fishing to deeper regions to exploit the oceanic fishery resources with improved infrastructure through policy interventions.

- The computed potential yield for the commercially exploited fishery resources could be taken as Biological Reference Points, BRPs/Fishery Harvest Limits, FHLs in the region. The Potential Yield was used to compute the optimum fishing fleet for different fishing crafts in the region.
- The study recommends the length based stock assessment, especially to species in overfished categories to understand the type of overfishing i.e. growth or recruitment overfishing. The study also suggest for the continuous monitoring of overexploited resources with proper management strategies to avoid the resource depletion.
- The study highlight the need to log-book system on board with haul wise details of at least coordinates, major catches (in weight) and total discards, especially for multiday fishing fleet. The real-time geo-coordinated fishery data could make the marine spatial and fishery management plans more robust.

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Immediate outputs and outcome of the research

Publications - Peer-Reviewed Journals

- Vase, V. K., Dash, G., Sreenath, K. R., Shailendra, R., Mohammed Koya, K., Divu, D., Dash, S., Pradhan, R. K., Sukhdhane, K. S., & Jayasankar J. (2018). Spatio-temporal variability of physico-chemical variables, chlorophyll a, and primary productivity in the northern Arabian Sea along India coast (2018). *Environmental Monitoring and Assessment* 190:148.
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Participation and presentation of Papers in International and National Forums

- 11th Indian Fisheries and Aquaculture Forum (Kochi, India during 21-24 November 2017): presented a paper entitled "Potential marine fishery yield for Gujarat state was estimated using the Surplus Production Models (Schaefer and Fox models)".
- 2nd International Symposium on Remote Sensing for Ecosystem Analysis and Fisheries (during January 15-17, 2018, Kochi, India). "Additive influence of nutrients on primary productivity along the northeastern Arabian sea".
- International Symposium on Marine Ecosystems Challenges & Opportunities (during 8-10 January 2020, Kochi, India): presented a paper entitled "Passive geo referencing of available historic data for reconstruction of spatial and temporal dynamics of mechanized trawl fishery in Gujarat".
- International Symposium on Marine Ecosystems Challenges & Opportunities (during 8-10 January 2020, Kochi, India): presented a paper entitled "Probable trawl fishing grounds in Indian EEZ: a passive geo-referencing approach".
- International Symposium on Marine Ecosystems Challenges & Opportunities (during 8-10 January 2020, Kochi, India): presented a paper entitled "Assessment of the trend and status in dolnet fishery along the Gujarat coast of India using holistic model".
- International Symposium on Marine Ecosystems Challenges & Opportunities (during 8-10 January 2020, Kochi, India): presented a paper entitled Status of marine fishery resources in the southwest coast of India by modelling stock biomass dynamics in a multi-gear fishery".

Publications - Scientific Meeting Documents/Contributions

- **Vase, Vinay Kumar** and Ramani, K., and Jayasankar, J (2017). Marine fish landings in Gujarat during 2016 - An overview. *Marine Fisheries Information Service*; Technical and Extension Series (233). pp. 6-8. ISSN 0254-380 X

Publications - Papers /Books under Publication/Review

- **Vinaya Kumar Vase**, Mohammed Koya, K., Dash, Swatipriyanka Sen, Dash,Gyanaranjan, Divu D., Rajesh K. Pradhan, Sreenath R., Abdul Azeez, P., Rajan Kumar, Rahangdale, Shikha, Tarachand Kumawat, Kapil S. Sukhdhane, Zacharia, P. U. (2019). Management Plans for the Marine Fisheries of Gujarat. ICAR-CMFRI Marine Fisheries Policy Series No. 16, 150pp.

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Spatio-temporal variability of physico-chemical variables, chlorophyll a, and primary productivity in the northern Arabian Sea along India coast

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Abstract The present study attempts to understand the seasonal and spatial variations in the physico-chemical (temperature, pH, salinity, dissolved oxygen, and nutrients) and productivity characteristics of the northern Arabian Sea off the Indian coast. Samples were collected from four different sites off the Veraval coast. The values of the physical and chemical variables were higher during the summer season, whereas nutrient concentrations were high during the winter season due to the maturity of intake nutrients during post-monsoon and winter convective mixing during the northeast monsoon. The dissolved oxygen (DO) concentration was strongly and positively correlated with the net primary productivity (NPP) and chlorophyll *a* (Chl-*a*) content to support productivity along the region. Dissimilarity in study variables was observed between the inshore and offshore locations. Principal component analysis revealed a strong relationship between nutrients and productivity variables (Chl-*a* and NPP). Nutrient levels were high at inshore sites, which can be attributed to the heavy nutrient load from land-based anthropogenic activities and impact due to natural processes like water mixing, sedimentation, and wave activities. Nutrients were strongly and positively correlated with the productivity variables, i.e., Chl-*a* and NPP. Chl-*a* positively correlated with NPP ($r = 0.90$), which indicates that it is a principle productivity pigment in the marine ecosystem.

Keywords Hydrological variables · Nutrients · Biological productivity · Inshore and far shore waters

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Introduction

Characteristic of any hydro-ecosystem depends mostly on various factors like physical and chemical variables, the source of pollution load, nutrient content, and availability of biomass. To understand the dynamics in the ecosystem, continuous monitoring of these variables is necessary. The variables like temperature, dissolved oxygen, pH, salinity, nutrient concentrations, and chlorophyll content directly or indirectly influence the primary productivity of the ecosystem, which is the base and prime components of the trophic pyramid in the marine ecosystem. Among all these variables, nutrient levels in water are the most important, which directly determines the productivity of the ecosystem. Nutrient uptake

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Potential Yield Estimates for marine fisheries of Gujarat

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Original Article

Abstract

Gujarat is the leading maritime State in marine capture fisheries in the country with current (2018) contribution of 7.80 lakh tonnes. The landings and fishing effort spent has escalated by 46.34% and 25.46% respectively since 1994. The study estimated the potential yield (maximum sustainable yield) for the 24 resource groups by using catch and standardized effort (a modified version) as input into the surplus production model. The current fish catch to potential yield ratio (Y_{cur}/MSY) was found to be in the range of 0.25-1.54 for the groups, with maximum fishing pressure experienced by silverbellies. The overall potential yield estimated for the State was 9.20 lakh tonnes plus, which is higher than the present catch of 7.80 lakh tonnes. The current situation offers an opportunity to further increase the catch with an increased effort by reducing the fishing pressure in territorial waters. However, fishing effort can be raised for the underexploited large pelagic resources like tuna, seerfish, barracudas, large carangids, etc., which are captured mainly by large mesh gillnet or long lines in the region. The study also recommends

Introduction

India is a leading nation in the Indian Ocean region in marine fish harvest from the wild, harvesting an estimated 3.49 million tonnes (FAO, 2018; CMFRI, 2019). The fishery production from the wild, in general, has increased over the years owing to the advancement in terms of number, power and endurance of the fishing fleet, duration of fishing voyage and improved processing and supply chain for the fishery products. The state of Gujarat, along the west coast of India, witnessed remarkable development in the marine capture fisheries sector. The State is naturally gifted with abundant marine fishery resources, 1600 km long coastline, 2 lakh km^2 of the exclusive economic zone and a shelf area of 1.64 lakh km^2. The abundance of easily accessible fishery resources, together with the strong fishing fleet of 28,400 (DAHDF and CMFRI, 2012), dominated by multi-day trawlers has allowed the State to surpass all other maritime states of the country in recent years in the marine capture fisheries production. The present contribution of the State to national marine capture fisheries

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Fishery and estimation of potential yield of Bombayduck *Harpadon nehereus* (Hamilton, 1822) along Gujarat coast, India

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ABSTRACT

Bombayduck *Harpadon nehereus* (Hamilton, 1822) is one of the key fishery resources landed along the Indian coast with uniqueness in distribution and exploitation. The resource is known for discontinuous distribution, majorly along the north-west and north-east coasts of India. Gujarat is the lead state to contribute nearly 64.72% (72,949 t) to the total national landings of the resource (11,2705 t) in 2018. Dolnet gear contributes nearly 95% of the total landings of the resource in the region. The landings and the corresponding catch per unit effort (CPUE) showed a fluctuating trend over the study period of 1994-2014. The catches fluctuated between 35,235 t (2016) and 92,188 t (2004), whereas the CPUE oscillated in the range of 15 to 20 kg h^{-1} (1998) and 30.76 kg h^{-1} (2003). The period of 1994-2000 was the most productive period with an average catch of 72,133 t, whereas the succeeding decade was the leanest phase with an average annual catch of 50,035 t. The estimated potential yield (= maximum sustainable yield, MSY) was estimated at 73,700 t and 70,108 t using the Bayesian surplus production model (CMSY & BSM) and basic Schaefer surplus production model respectively. The present catch and exploitation levels were found to be close to the optimum level and a further increase in effort for the resource is not recommended.

Keywords: Bombayduck, BSM, CMSY, *Harpadon nehereus*, Median catch, Surplus production model

Introduction

The Bombayduck *Harpadon nehereus* (Hamilton, 1822) is a unique fishery resource with discontinuous distribution along the Indian coast. The availability is restricted along the north-west and north-east coasts of India. North-west coast of India contributes to bulk of the total Bombayduck landings. Fishery for the resource is traditional to the state of Gujarat, especially along the south Gujarat and Saurashtra region, where the resource is harvested using a specialised type of bag net referred to as dolnet. The species is locally called as *Bumla* or *Bumli* and is preferred in fresh, salted and dried form. Laminated version of dried Bombayduck is a preferred commodity, study of the fishery and biology of the species in India. Bapat (1967, 1970) has established the fact that the stocks harvested in both Gujarat and Maharashtra coasts are not similar, hence they need separate management strategies. Since then, several parallel studies have been conducted on the species along both the coasts. Several works on feeding biology (Khan *et al.*, 1992; Ghosh *et al.*, 2009), reproductive biology, age, growth and mortality (Khan, 1989; Khan *et al.*, 1992; Ghosh *et al.*, 2009; Ghosh, 2014) were carried out for the resource along the Gujarat coast.

The fishery of Bombayduck, though has been underexploited for a long time, currently needs periodic assessment on the health status of the stocks with ever-

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Temporal dynamics of primary productivity in the north-eastern Arabian Sea: an evaluation of ocean color models

Vinaya Kumar Vase ✉, Nakhawa Ajay, Rajan Kumar, Sreenath Ramanathan, Jayasankar Jayaraman & Prathibha Rohit

Arabian Journal of Geosciences 14, Article number: 1338 (2021) | Cite this article

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Abstract

We examined the spatial and temporal variations in monthly primary productivity (PP; mg C m^{-2} day^{-1}) in the northern Arabian Sea from 2015 to 2017 using the PP model (Vertically Generalized Production Model, VGPM) to identify and tag productivity zones and seasons. The major objective was to validate the existing satellite algorithms and compare them with the regional parameterization and further define the most accurate model for the region. The models use both in-situ chlorophyll-*a* (Chl-*a*), SST, and euphotic depth (Z_{eu}) (derived from Chl-*a*), and satellite-retrieved (photosynthetically available radiance, PAR and day length, DL) variables as input parameters. The measured PP values showed significant intra-annual variations, and the maximum was during December (3689.2 ± 505.3 mg C m^{-2} day^{-1}) and the minimum during August (2207.7 ± 202.2 mg C m^{-2} day^{-1}). The linear regression depicted that the input variables (Chl-*a*, PAR, Z_{eu}, DL) together explained 48.68% variation in the PP. The chlorophyll-*a* showed significant variability in PP, followed by DL, PAR, and Z_{eu}. We tested three modified models with minor modifications in input variables of basic VGPM. Among the models validated in the region, the VGPM-KI could explain 38.3% of the variance with the in-situ PP data, followed by other models (range of variance explained from 18.7 to 38.3%). The average model precision, as determined by RMSD and the bias, was lowest for the modified model (VGPM-KI, VGPM-BF, and VGPM-E), but highest in case of models with satellite as a sole source of input variables (VGPM and EVGPM). In the northern Arabian Sea, VGPM-KI and VGPM-E performed better than the other models. However, VGPM-KI overestimated the PP values when compared to in-situ estimates. The biogeochemical cycles and ocean processes like coastal upwelling and winter convection by winds, which are the key determiners for perennial productivity in the region, will also affect PP in the region.

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The molecular identification of three species of deep sea caridean shrimps under two genera: Acanthephyra and Plesionika were studied. The genus Acanthephyra includes two species viz., *A. fimbriata* and *A. sanguinea;* the genus *Plesionika* includes one species, *P. narval*. The samples were collected by trawl nets operated at depth range of 200-350 m from two locations along the southwest coast of India. Molecular analyses of the samples were carried out using two genes: mitochondrial cytochrome c oxidase subunit 1 (COI) and 16S rRNA. The genetic distance and their phylogenetic relationship with other representatives from the same genus were also analyzed. Sequences were submitted in GenBank and retrieved accession numbers of these species. The accession numbers of the species, *A. fimbriata* (COI: KU055638, KU055639, MF627725, MF627726; 16S: KU055642, KU055643), *A. sanguinea* (COI: KU055644, KU055645, MF627727,

FR PO 27

Estimation of potential yield and optimum fishing effort for the marine fisheries of Gujarat

VINAYA KUMAR VASE[1]*, MOHAMMED KOYA[2], K. GYANARANJAN DASH[1], SWATIPRIYANKASEN DASH[1], D. DIVU[1], J. JAYASANKAR[2], PRATHIBHA ROHIT[3]

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The potential fishery yield is the key management input for the optimal exploitation and sustainable management of the fishery resources. Commercially exploited fishery resources were grouped into five realms along the region viz., small pelagic, large pelagic, demersal, crustaceans and mollusks. Fishing effort (active fishing hours) was standardized based on the weighted catch per unit effort (CPUE) for the

major fishing gears viz., mechanized trawl net (MTN), mechanized gillnet (MGN), mechanized dollnetter (MDOL), motorized gillnet (MRGN) and motorized dollnetter (MRDOL). The major fishing gears were contributing more than 98% of the marine fish landings of the region. Realm wise catch and standardized fishing effort was taken as input data to run the surplus production models for the period of ten years (2006-2015). Estimated potential yields (MSY) for the different realm categories were viz., small

Results of a pioneering study, comprehensively dealing with the fish diversity of a lesser studied estuary is presented. Poonthura estuary located in Thiruvananthapuram district is a highly polluted sand bar estuary providing livelihood support to fishermen of adjacent areas including migrants and part time fishermen. During the period of 12 months from June 2016 to May 2017, a total of 51 species, comprising 46 finfish and 5 shellfish species belonging to 8 orders and 30 families were

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Additive influence of nutrients on primary productivity along the northeastern Arabian Sea

Vinaya Kumar Vase[1]*, Gyanaranjan Dash[1], Sreenath K. R[1]., Ganesh T[1]., Shailenda R[1]., Bhargav B.[1], Mohammed Koya[2], K., Divu D[1]., Kapil S. Sukhdhane[1], Abdul Azeez P.[1], Jayasankar J.[2] and Mini Raman[3]

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Bio-geologically significant nutrients like nitrates, phosphates and silicates were analyzed to study the additive influence on the productivity of the ecosystem. Chlorophyll-a (Chl-*a*) is a principal productivity pigment present in the marine ecoregion, which is considered as a proxy for productivity. Sampling was carried along off Gujarat coast of Arabian Sea, from October 2013 to March 2017 (N=90). Generalized Additive Models (GAM) were known to back fitting the algorithm to combine different smoothing or fitting methods. The statistical methods currently supported are local regression and smoothing splines. GAM is used to models, specified by giving a symbolic description of the additive predictor and a description of the error distribution. In the current study, the model is used to fit the algorithm between nutrients (silicates, phosphates and nitrates) as independent parameters and chl-*a* dependent (predictor) parameter. Regression parameters for the model are intercept (-0.12731) and slopes (silicates -0.03306; phosphates 8.44213; nitrates 0.22808). Nutrients like phosphates and nitrates were found to have significant impact ($p<0.001$) on Chl-*a*, whereas silicates did not have any significant impact. Finally, the three nutrients together explained 56.80% of deviance on Chl-*a*. Results conclude that the studied nutrients, *i.e.*, nitrates and phosphates are showing significant impact on the productivity along the study region. Phosphates ($Pr>|t| = 1.65e-10$) are showing strong positive significant impact than nitrates ($Pr>|t| = 4.07e-07$), which proves that phosphates are acting as limiting nutrients along the region.

Keywords: Chlorophyll-*a*, GAM model, Phosphates, Nitrates, Northeastern Arabian Sea, Primary productivity

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Status of marine fishery resources in southwest coast of India by modelling stock biomass dynamics in a multi-gear fishery

Sathianandan T. V.*, Mohamed K. S., Jayasankar J., Somy Kuriakose, Mini K. G., Eldho Varghese, Zacharia P. U., Prathibha Rohit, Maheswarudu G., Vijayakumaran K., Kaladharan P., Najmudeen T. M., Mohamed Koya K., Sivadas M., Shoba Joe Kizhakudan, Geetha Sasikumar, Ganga U., Sujitha Thomas, Lakshmi Pillai S., Grinson George, Vinay Kumar Vase, Vivekanand Bharti, Sreepriya V., Alphonsa Joseph and Deepthi A.

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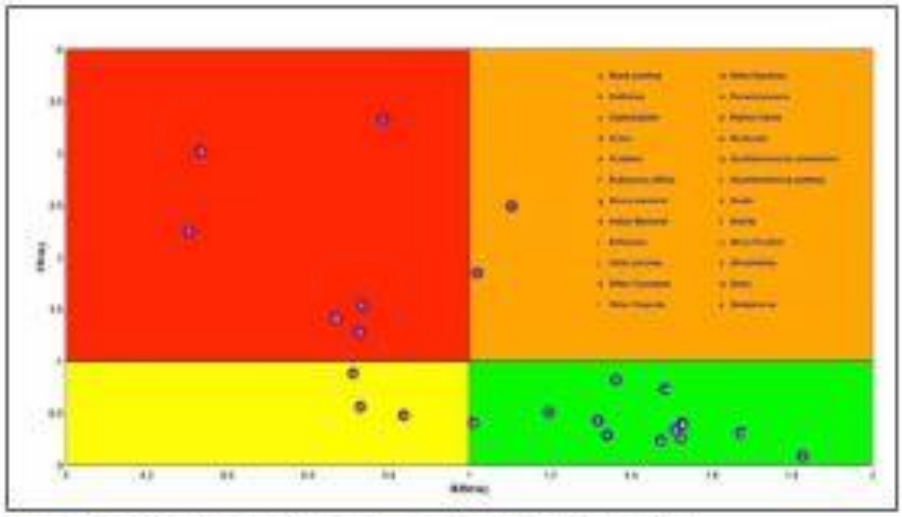
The marine fisheries sector in India contribute significantly to the food and nutritional requirements of its people and support livelihood of nearly four million fisher population in addition to foreign exchange earnings through export. Nearly 33 % of the marine fish production is from the southwest coast comprising the states of Kerala, Karnataka and Goa which is only 16.4% of the total coastline. Harvest of the marine fishery resources requires proper control through appropriate management measures for sustainability of the resources. The most commonly used management reference point, maximum sustainable yield (MSY), is derived here for all the important marine fishery resources in these states considering the multi-gear fishery and adopting suitable biomass dynamic modelling approach with time series data on gear wise fish catch and fishing effort as input sourced from the National Marine Fishery Resources Data Centre (NMFDC) of ICAR-Central Marine Fisheries Research Institute.

In the modelling approach, the multi-gear situation was handled by incorporating a set



Kobe plot showing stock status of 24 resources examined in the fishery in Kerala

Assessment of the trend and status in dolnet fishery along the Gujarat coast of India using holistic model

Vinay Kumar Vase*, Rajan Kumar, Mohammed Koya, Shikha Rahangdale, Azeez A., Prathibha Rohit, Jayasankar J., Zacharia P. U., Ajay D. Nakhawa, Kapil S. Sukhadhane and Divu D.

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The Dolnet fishing along the northwest coast of India is a traditional one and unique in many ways. Gujarat is the lead maritime state of the country in dolnet fishing. The Dolnets in the region are operated by both the mechanized and motorized dolnetters. The overall length (OAL) of dolnetter's range between 12 and 14 m and powered with an engine of 85-110 HP. Dolnetters contributed significantly to the total marine fish landings of Gujarat during 2018 with a contribution of 2.9 lakh t (37.20%). The non-penaeid prawns (0.72 lakh t) were the major resource in the dolnet during the study period, followed by bombayduck (0.56 lakh t), croakers (10.60 lakh t), ribbonfish (0.096 lakh t), penaeid prawns (0.091 lakh t), catfishes (0.088 lakh t) and golden grenadier(0.077 lakh t). A major portion of the dolnet catch is utilized for drying (non-penaeid prawns, bomdayduck, golden grenadier and small sized ribbonfish). A large percentage of the dried fishes are used for preparation of fish meal and lower volume for domestic consumption. The catch and effort data (in fishing hours) for the dolnet fishing during 2004-2018 was used as an input in the Schaefer surplus production model. The maximum catch was recorded during 2018 (2.90 lakh t) and minimum during 2004 (0.84 lakh t). Highest fishing effort (hrs) was recorded in 2017 (43.53 lakh hrs) and the lowest during 2013 (15.81 lakh hrs). MSY was estimated at 2.775 lakh t for the State which is marginally higher than the average catch (2.773 lakh t) of last three years. Dolnet is a passive gear and fishing mostly depends on the current movement restricting the option of shift in fishing grounds. Therefore the only management option left with is the control over the mesh size of the gear and number of fishing units. The present investigations infer that the exploitation limit can be fixed to the estimated MSY and more investigations on catch composition and mean size of the individual resources need to be done to understand the health status of individual fish stocks and also to frame management strategies for the long-term sustainability of the fishery.

Probabale trawl fishing grounds in Indian EEZ: a passive georeferencing approach

Jayasankar J., Eldho Varghese*, Sathianandan T. V., Somy Kuriakose, Mini K. G., Grinson George, Vivekanand Bharti and Vinay Kumar Vase

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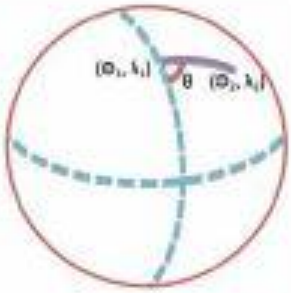
In India, marine fishery sector provides direct employment to one million people and indirectly supports another half a million people through allied activities. So protecting fishery resources through sustainable harvest is utmost important for the sustainable livelihood of coastal fishers. To this end, assessment of the availability of the marine resources will be helpful in deriving management plans by ensuring the sustainable harvest of the resources. Geographic Information System (GIS) tools are very useful in fishery management for mapping of habitats, georeferencing information on catch and effort and linking catch with the oceanographic and biochemical factors. This is possible when the resource habitat information is available on a spatial scale. In India, landing centre based surveys are commonly practised to make an assessment of resources, as the exploratory fishery resources surveys are much time consuming and expensive. In such surveys, lack of geo-tagging of the resources observed at landing centre makes it difficult for the mapping of the habitat. Usually the landings record have information about bearing and the distance covered by the craft surveyed and using the following Haversine formula, for finding the destination coordinates given distance and bearing from start point coordinates, probable latitude and longitude of the fishing grounds can be obtained:

$$\phi_2 = \arcsin\left[\sin\phi_1 \cdot \cos\delta + \cos\phi_1 \cdot \sin\delta \cdot \cos\theta\right]$$

$$\lambda_2 = \lambda_1 + \operatorname{atan2}\left(\sin\theta \cdot \sin\delta \cdot \cos\phi_1, \cos\delta - \sin\phi_1 \cdot \sin\phi_2\right)$$



Where ϕ is latitude, λ is longitude, θ is the bearing (clockwise from north), δ is the angular distance d/R; d being the distance to destination, R the earth's radius (mean radius = 6,371km), 'asin' is arcsine (i.e. the inverse sine) of a given number and 'atan2' is the arctangent (or inverse tangent) of the specified x- and y-coordinates.

In this paper, attempt has been made to find the probable trawl fishing grounds (spatial coordinates) using information on bearing and distance from landing centre of trawlers operated in the Indian Exclusive Economic Zone (EEZ) during the year 2018. This has been done separately for single day trawl net (MTN) and multiday trawl net (MDTN) and presented in Fig. 1.

Passive geo referencing of available historic data for reconstruction of spatial and temporal dynamics of mechanized trawl fishery in Gujarat

Vinay Kumar Vase*, Rajan Kumar, Jayasankar J., Ajay D. Nakhawa, Mohammed Koya, Shikha Rahangdale, Kapil S. Sukhadhane, Divu D. and Prathibha Rohit

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Marine ecosystems and resources are under severe threat due to increase in pollution, coastal development projects, natural calamities and the fishing activities. Fishing especially trawling has a detrimental impact on the biodiversity, all the more if the trawling is made in ecological sensitive habitats (coral reefs, sea grass beds, mangroves, etc.). In addition, trawling can lead to overfishing of commercially exploited resources, juvenile and spawner's, increased exploitation of by-catch and threatened species. Our country is far behind in the spatial mapping of the marine fishery resources and fishing grounds and is still a nacent field in India as compared to other developed countries. Further it is all the more complex in India due to the unorganized fishery structure and as laggard in technology adoption and diverse in both resources and crafts. In this context, the present piece of work provides a way to map the fishing grounds with the available historic fishery data to understand the spatial and temporal spread of fishing activity. This passive geo-referencing method was used to map the fishing pattern of Mechanized Trawlers, MTN (operate for single day)using the available fishery data for 12 fish landing centers in Gujarat (N=2678). The distance of the fishing grounds from the landing center/ barmouth ranged from 4 to 75 km (mean ± sd; 18.06 ± 9.86 km). The average depth of operation was 26.57 ± 9.0 m (5 to 80 m with an inter quantile range of 12 m). The catch rates (Catch Per Unit Effort, CPUE in kg/hrs) were higher in the MTN than the other fishing crafts due to the active fishing and retention of whole exploited catch (negligible discards). The catch rates recorded in the study period ranged from 17 to 689 kg/hr (mean ± sd; 86.36 ± 91.20 kg/hr with an inter quantile range of 63.30 kg/hr). The catch rates were highly dynamic in nature both in spatial and temporal scales. One-way ANOVA infer the significant variations in catch rates among different quarters ($p<0.005$). The mean CPUE was highest during the quarter I (101.80 kg/hr), followed quarter II (94 kg/hr), quarter III (82.65 kg/hr) and quarter IV (72.54 kg/hr). The catch rates were comparatively higher in the quarter I due to the significant contribution by the fishery resources like non-penaeid prawns, croakers, ribbonfishes, etc. The non-penaeid contribution by the MTN was visible in a target mode during February to May months, which requires a focussed investigation and management interventions. The information on fishing practices is missing in various development plan approvals in India, which often lead to unanticipated conflicts in the sea, competing for space and resources. The spatial intensity of the fishing crafts depicted that the fishing pressure in the different fishing grounds, continuation of effort in such areas may lead to steno-productivity zones due to the depletion of resident resources and stability of ecosystems. In future, the resource-wise catch composition of the fishing ground data can be generated to understand the spatial and temporal abundance of the resources, which in turn can be used to comprehend the migration patterns and environmental impacts on the resources

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